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Comparative Study of Cold In-Place Recycling and Hot Mix Asphalt for Road Rehabilitation in Nigeria: A Cost-Benefit Analysis

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Abstract

Nigeria's extensive road network faces severe deterioration due to chronic under-maintenance, overloading, extreme weather, and funding constraints. Traditional Hot Mix Asphalt (HMA) rehabilitation, while widely used, is resource-intensive, costly, and environmentally burdensome. This study conducts a comprehensive comparative analysis of Cold In-place Recycling (CIR) and HMA for pavement rehabilitation in Nigeria, focusing on technical performance, lifecycle costs, and cost-benefit outcomes under local conditions. Employing a mixed-methods approach, the research integrates literature review, case studies across geo-political zones, Lifecycle Cost Analysis (LCCA), and Cost-Benefit Analysis (CBA) using metrics such as Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR) over a 20-year period. Data sources include secondary reports from federal agencies, international benchmarks adjusted for Nigeria, and stakeholder insights. Findings reveal that CIR offers 20-50% initial cost savings, lower lifecycle and user costs, reduced construction disruptions, and superior environmental benefits (23% lower CO_2 emissions and significant virgin material conservation). CIR demonstrates higher NPV and BCR (1.8-3.2) compared to HMA, proving more economically viable for medium- and low-volume roads, though hybrids may suit high-traffic corridors. Challenges include limited expertise, equipment availability, and weather dependency for CIR. The study recommends greater adoption of CIR to optimize budgets, enhance sustainability, and address infrastructure deficits.

Keywords: Cold in-place recycling, Hot mix asphalt, Road rehabilitation, Cost-benefit analysis, Lifecycle costing, Pavement recycling.

1 | Introduction

Nigeria possesses one of the largest road networks in Africa, with approximately 194,000 km of roads, of which only about 30,000 km are paved. Federal roads alone span around 36,000 km. For decades, this critical infrastructure has suffered from chronic under-maintenance, leading to widespread deterioration. Factors

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such as inadequate funding, overloading of vehicles, poor drainage, extreme weather conditions (heavy rainfall and high temperatures), and rapid urbanization have accelerated pavement distress, including cracking, rutting, potholes, and structural failures [1], [2]. The economic implications are severe. Poor road conditions impose massive costs on the economy, with studies estimating annual losses to road freight systems alone at around $7.8 billion (roughly 1.6% of Gross Domestic Product (GDP)). Additional burdens include higher Vehicle Operating Costs (VOC), increased travel times, and reduced trade efficiency. Successive governments have allocated significant budgets to road projects (over ₦1 trillion in recent years), yet the maintenance funding gap remains wide experts suggest an annual requirement of at least ₦880 billion for effective upkeep, far exceeding consistent budgetary provisions [3], [4].

Traditional road rehabilitation in Nigeria relies heavily on Hot Mix Asphalt (HMA) overlays or reconstruction. This method involves producing new asphalt mixtures at high temperatures, transporting materials, and laying them on prepared surfaces. While effective in providing strong, durable surfaces, HMA is resource-intensive, energy-consuming, and generates substantial greenhouse gas emissions [5], [6]. In contrast, Cold In-Place Recycling (CIR) is an emerging sustainable alternative. CIR reuses the existing pavement material on-site by milling, stabilizing (often with cement, emulsion, or foamed bitumen), and compacting it without heating. This process offers potential advantages in cost savings (often 20-50% compared to conventional methods), reduced material consumption, lower environmental impact, and faster project delivery with minimal traffic disruption. Globally, CIR has gained traction for its economic and ecological benefits, particularly in resource-constrained environments. However, its adoption in Nigeria remains limited due to factors such as limited technical expertise, equipment availability, climatic suitability concerns, and a preference for conventional HMA approaches [7]. This study examines these two methods within the Nigerian context through a comprehensive cost-benefit lens.

1.2 | Issue Description

Nigeria's road infrastructure crisis persists despite substantial investments. Many rehabilitated roads fail prematurely, leading to repeated expenditures that strain limited public resources. Conventional HMA rehabilitation, while widely used, faces challenges including high initial costs, heavy reliance on imported or scarce virgin materials (bitumen and aggregates), significant energy use, and substantial carbon emissions from production and transportation [8], [9]. CIR offers a promising alternative by recycling existing pavement in situ. Yet several critical questions remain unanswered in the Nigerian setting:

I. How do the lifecycle costs of CIR compare with HMA under local conditions (climate, traffic loads, soil types, and material availability)?

II. What are the technical performance differences in terms of durability, strength, and maintenance needs?

III. To what extent can CIR deliver superior cost-benefit outcomes, including reduced user costs, environmental benefits, and long-term economic returns?

There is a noticeable gap in context-specific research and empirical data comparing these techniques in Nigeria. This knowledge deficit hinders evidence-based decision-making by policymakers, road agencies (such as the Federal Ministry of Works and FERMA), and contractors. Without rigorous comparative analysis, the country risks continued over-reliance on expensive, less sustainable methods amid growing fiscal pressures and sustainability imperatives. This study aims to conduct a comparative analysis of CIR and HMA for road rehabilitation in Nigeria, with a primary focus on Cost-Benefit Analysis (CBA) to determine the more economically viable, technically suitable, and sustainable option under Nigerian conditions [10], [11] which; objectively will:

I. Review the principles, processes, advantages, and limitations of CIR and HMA technologies in pavement rehabilitation.

II. Assess the technical performance and suitability of both methods in the Nigerian climatic, traffic, and geotechnical context.

III. Evaluate and compare the initial construction costs, lifecycle costs, and maintenance requirements of CIR versus HMA.

IV. Perform a detailed CBA, including Net Present Value (NPV), Benefit-Cost Ratio (BCR), Internal Rate of Return (IRR), and sensitivity analysis [12].

V. Analyze environmental and socio-economic benefits (reduced emissions, material conservation, traffic disruption, and user costs).

VI. Identify implementation challenges and recommend policy and practical strategies for wider adoption of the more beneficial technique in Nigeria.

The study holds substantial importance for multiple stakeholders in Nigeria's infrastructure sector. As the country grapples with a massive road infrastructure deficit and limited public resources, identifying cost-effective and sustainable rehabilitation methods is critical for maximizing value from available funds [13]. The findings will provide empirical evidence to guide policymakers and road agencies (Federal Ministry of Works, Federal Roads Maintenance Agency (FERMA), and State Ministries) in selecting appropriate technologies for pavement rehabilitation. By demonstrating potential cost savings (potentially 20-50% through CIR compared to traditional HMA in suitable conditions), the study can contribute to more efficient budget allocation and help close the significant maintenance funding gap as follows:

I. For the construction industry and contractors, the research offers insights into the technical feasibility, equipment requirements, and skill needs for adopting CIR, potentially fostering local capacity building and technology transfer. This could reduce dependence on costly imported materials and promote indigenous innovation in road construction.

II. Environmentally, the study highlights the sustainability benefits of CIR, such as reduced energy consumption, lower greenhouse gas emissions, and conservation of virgin aggregates [14]. This aligns with Nigeria's commitments to climate action and sustainable development goals, providing data that can support greener public procurement policies.

III. Academically, the research fills a critical knowledge gap by providing context-specific comparative data on CIR and HMA in tropical developing country conditions. It will serve as a reference for future studies on pavement engineering, lifecycle costing, and sustainable infrastructure in Nigeria and similar African nations.

Ultimately, successful implementation of the recommended approach could lead to improved road quality, reduced VOC, enhanced road safety, better trade facilitation, and broader economic growth. The study therefore contributes to both immediate infrastructural efficiency and long-term national development objectives and also focuses on a comparative evaluation of CIR and conventional HMA for the rehabilitation of existing flexible pavements in Nigeria [15]. The analysis centres on cost-benefit parameters, including initial costs, lifecycle costs, maintenance needs, user costs, and environmental externalities.

Geographically, the research draws on case studies or data from representative Nigerian road projects, primarily federal and state highways in different geo-political zones to account for variations in climate, traffic volume, and soil conditions. The technical comparison covers material properties, construction processes, performance, and durability. The CBA employs standard economic evaluation tools such as NPV, BCR, and sensitivity analysis over a typical 15-20 year analysis period. The study incorporates both secondary data (existing literature, project reports, and official statistics) and, where feasible, primary data from selected ongoing or completed rehabilitation projects.

1.3 | Research Limitations

Data availability: Access to comprehensive, up-to-date cost and performance data for CIR projects in Nigeria may be limited due to the relatively low adoption rate of the technology. The study will rely partly on international benchmarks adjusted for local conditions, which may introduce some estimation uncertainty.

Time and resource constraints: As a research project, the scope is restricted to available time and budget. Long-term field performance monitoring (beyond 5-10 years) of CIR sections in Nigeria may not be fully captured.

Variability of conditions: Nigerian roads exhibit high heterogeneity in traffic loading, subgrade strength, rainfall patterns, and maintenance history. While efforts will be made to select representative cases, findings may not be universally applicable to all road types (very high-traffic expressways or low-volume rural roads) [16].

External factors: Economic variables such as inflation, foreign exchange fluctuations (affecting equipment and material costs), and policy changes could influence the cost-benefit outcomes. Sensitivity analysis will be used to mitigate this.

Technical expertise: Limited local experience with CIR means that some assumptions regarding constructability and long-term performance will be based on global best practices adapted to Nigerian contexts.

2 | Overview of Road Rehabilitation Methods in Developing Countries

Road infrastructure in developing countries faces unique challenges, including limited funding, rapid traffic growth, extreme climatic conditions, and inadequate maintenance regimes [17]. Common rehabilitation methods include reconstruction, overlaying, mill and fill, surface treatments (such as chip seals or slurry seals), and various recycling techniques.

Traditional approaches like full-depth reconstruction or thick HMA overlays dominate due to familiarity and established supply chains [18]. However, these methods are capital-intensive and often unsustainable given budget constraints. Studies across Africa, Asia, and Latin America highlight that many developing nations spend a disproportionate share of transport budgets on new construction while neglecting maintenance, leading to premature pavement failure and higher long-term costs.

In-situ recycling technologies including CIR, Hot In-place Recycling (HIR), and Full-Depth Reclamation (FDR) have gained attention as sustainable alternatives. These methods reuse existing pavement materials, reducing the need for virgin aggregates and bitumen, lowering transportation costs, and minimizing environmental impacts [19]. In countries like India, South Africa, and parts of Latin America, CIR and similar cold recycling techniques have demonstrated 20-50% cost savings compared to conventional methods while extending pavement life.

In the Nigerian context, rehabilitation has historically relied on HMA overlays amid chronic underfunding and material scarcity. The adoption of recycling technologies remains low due to limited technical capacity, equipment availability, and regulatory frameworks, despite their potential to address the country's infrastructure deficit more efficiently.

2.1 | Principles and Processes of Cold In-place Recycling

CIR is a pavement rehabilitation technique that reuses the existing asphalt pavement on-site without the application of heat [20]. The process typically involves the following steps:

I. Milling: A specialized recycler mill pulverizes the existing asphalt layer (usually 50-150 mm depth) along with some underlying base material.

II. Stabilization/additive introduction: The milled material (Reclaimed Asphalt Pavement (RAP)) is mixed with recycling agents such as asphalt emulsion, foamed bitumen, cement, or lime to improve binding and structural properties.

III. Compaction: The recycled mixture is laid and compacted using rollers to achieve required density.

IV. Curing: The stabilized layer requires a curing period (typically 3-14 days) before a wearing course (asphalt overlay, chip seal, or surface treatment) is applied.

2.2 | Principles and Processes of Hot Mix Asphalt

HMA is the conventional asphalt paving method widely used globally. It involves producing a mixture of aggregates and bitumen at high temperatures (typically 150-180°C) in a central asphalt plant [21]. The processing steps include:

I. Material preparation: Virgin aggregates and bitumen (sometimes with RAP up to 20-30%) are heated and mixed in a batch or drum plant.

II. Transportation: The hot mix is transported to the site in insulated trucks.

III. Laying and compaction: The mixture is laid using pavers and compacted while still hot to achieve proper density and smoothness.

IV. Cooling and opening to traffic: The surface cools and gains strength before traffic is allowed.

HMA provides excellent structural capacity, ride quality, and durability, making it suitable for high-traffic roads. It is a mature technology with well-established standards, skilled workforce availability, and predictable performance. However, it is energy-intensive, generates higher emissions, requires substantial virgin materials, and involves longer project durations due to plant-to-site logistics. In Nigeria, HMA remains the default choice for major rehabilitation projects due to familiarity, but it faces challenges from high costs, bitumen price volatility, and frequent premature failures caused by poor underlying support or overloading [22].

2.3 | Comparative Technical Performance of CIR and HMA

Literature shows that both CIR and HMA can deliver satisfactory performance when properly designed and constructed, but they differ significantly in behaviour and application as follows.

I. Structural performance: HMA generally offers higher initial stiffness and load-bearing capacity, making it preferable for heavily trafficked routes. CIR, being a stabilized granular-like material, may exhibit lower early strength but can achieve comparable long-term performance when properly stabilized [23]. Studies report that CIR layers often have structural layer coefficients between 0.30-0.44, depending on additives.

II. Durability and distress resistance: Both methods effectively address surface cracking and rutting. CIR excels at mitigating reflective cracking by homogenizing the existing distressed layer. HMA performs well in high-temperature environments but is susceptible to fatigue cracking if the base is weak. In tropical climates, CIR's performance depends heavily on moisture resistance and curing quality.

III. Environmental and sustainability metrics: CIR consistently outperforms HMA, with reported savings of approximately 23% in energy consumption and CO_2 emissions, 20% in water use, and up to 37% reduction in virgin aggregate demand [24].

IV. Service life: When combined with an appropriate wearing course, CIR can extend pavement life by 10-20 years, comparable to or better than thin HMA overlays in many cases.

V. Suitability in developing countries: CIR offers logistical advantages in areas with limited plant access, while HMA benefits from established supply chains. Hybrid approaches (CIR base with thin HMA overlay) are increasingly recommended for optimal performance.

Overall, while HMA remains a robust solution for major arterial roads, CIR presents a technically viable, more sustainable alternative for many secondary and tertiary roads in resource-constrained settings like Nigeria. The choice ultimately depends on traffic volume, existing pavement condition, climate, and economic considerations.

2.4 | Cost Components and Economic Evaluation of Pavement Rehabilitation Techniques

Economic evaluation of pavement rehabilitation considers costs across the entire lifecycle. Major cost components include:

I. Initial agency costs: Material, labour, equipment, and mobilization expenses. HMA typically incurs higher costs due to virgin materials, heating energy, and transportation. CIR often achieves 20–50% savings by reusing on-site materials and reducing haulage.

II. Maintenance and rehabilitation costs: Future overlays, patching, or reconstruction needs. Techniques with better durability (often CIR when well-designed) reduce long-term interventions.

III. User costs: VOCs (fuel, tyres and maintenance), travel time delays, and accident costs during construction and over the pavement's life. CIR generally causes shorter disruptions.

IV. Salvage value: Residual value at the end of the analysis period.

V. External costs: Environmental damages, such as carbon emissions and resource depletion.

Lifecycle Cost Analysis (LCCA) is the standard approach for comparing alternatives. It discounts all future costs to present value using an appropriate discount rate (commonly 4-12% depending on the country's economic context) [25]. Studies consistently show that cold recycling methods like CIR yield lower total lifecycle costs than traditional HMA overlays, especially on medium- to low-volume roads.

2.5 | Cost-Benefit Analysis Frameworks and Methodologies

CBA extends beyond agency costs to quantify broader societal benefits. Common frameworks include:

I. Net Present Value: The difference between the present value of benefits and costs. A higher NPV indicates a more favourable option.

II. Benefit-Cost Ratio: Benefits divided by costs. A ratio greater than 1 indicates economic viability.

III. Internal Rate of Return: The discount rate at which NPV equals zero.

IV. Payback period: Time required to recover initial investment.

Benefits typically encompass reduced VOCs, time savings, accident reduction, environmental gains (e.g., lower emissions), and increased economic productivity from improved connectivity. Sensitivity and scenario analyses are essential to account for uncertainties in traffic growth, material prices, and climate impacts. International guidelines (e.g., from the World Bank, FHWA, and AASHTO) recommend these tools for infrastructure decisions in developing countries, where fiscal constraints make optimal resource allocation critical.

2.6 | Road Infrastructure Challenges and Rehabilitation Practices in Nigeria

Nigeria's road network suffers from decades of under-maintenance, overloading, poor drainage, and harsh environmental conditions. Only a small fraction of roads are in good condition, leading to annual economic losses estimated in billions of dollars. Rehabilitation practices remain dominated by conventional HMA overlays and spot repairs. While major projects receive attention, routine maintenance is chronically underfunded [26]. Government reports indicate a persistent gap between required (₦880 billion annually) and allocated maintenance budgets. Challenges specific to Nigeria include:

I. High bitumen and aggregate costs.

II. Seasonal flooding affecting pavement stability.

III. Limited local production capacity for advanced recycling additives.

IV. Shortage of skilled personnel and specialized equipment for modern techniques like CIR.

There is growing policy interest in sustainable methods, but implementation lags behind global trends.

3 | Research Methodology

3.1 | Research Design

This study adopts a mixed-methods comparative research design with a strong emphasis on quantitative economic evaluation. The design integrates descriptive, analytical, and evaluative approaches to achieve a comprehensive comparison between CIR and HMA for road rehabilitation in Nigeria. The quantitative component centres on LCCA and CBA to determine economic viability. Qualitative elements include a review of technical performance, implementation challenges, and stakeholder perspectives. This hybrid approach allows for triangulation of data, enhancing the validity and reliability of findings. The study follows a deductive strategy, starting from established theories and international best practices in pavement engineering and economic evaluation, then applying them to the Nigerian context through case studies. A comparative case study method is employed to analyze real-world rehabilitation projects using either techniques (or HMA as the baseline where CIR data is limited).

3.2 | Study Area (Selected Roads/States in Nigeria)

The study focuses on representative federal and state roads across Nigeria's six geo-political zones to capture climatic, traffic, and geological variations as shown in *Figs. 1* and *2*. Priority is given to:

I. Southwest (Lagos-Ogun-Oyo axis)-High traffic volume, urban influence, and coastal humidity.

II. Southeast/South-South (e.g., Enugu-Anambra or Rivers-Delta roads)-High rainfall, flood-prone areas, and oil-rich regions with heavy truck traffic.

III. North-Central/Northeast (e.g., Abuja-Kaduna or Bauchi-Gombe corridors)-Savannah climate with extreme temperature variations and lower rainfall.

IV. Northwest-Arid/semi-arid conditions with dust and high solar radiation

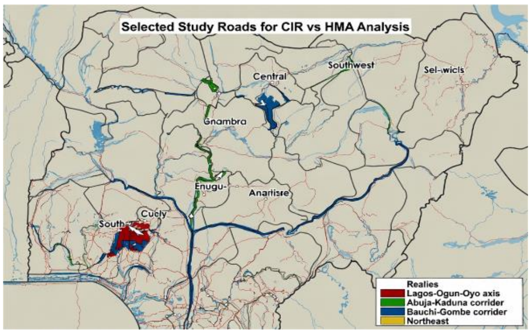

Fig. 1. Selected study corridors [24].

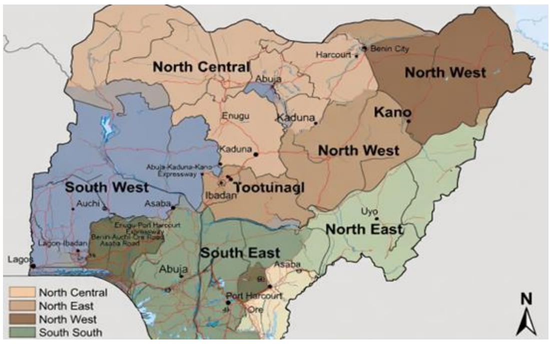

Fig. 2. Map of Nigeria showing Geo-Political Zones [27].

Specific roads were selected based on availability of rehabilitation history (preferably projects completed within the last 5-10 years) and data accessibility. This multi-regional approach ensures findings are generalizable across Nigeria's diverse conditions rather than being limited to one climatic zone [28].

3.3 | Data Collection Methods (Primary and Secondary Data)

Secondary data sources:

I. Official documents and reports from the Federal Ministry of Works, FERMA, and State Ministries of Works.

II. Project bills of quantities, cost data, and performance reports for HMA and any available CIR projects.

III. Academic journals, international pavement research (FHWA, World Bank, TRB), and previous Nigerian studies on road infrastructure.

IV. Economic data (discount rates, inflation, VOCs) from the Central Bank of Nigeria, National Bureau of Statistics, and relevant literature.

Primary data sources:

I. Structured questionnaires and interviews with key stakeholders (engineers from road agencies, contractors, consultants, and maintenance personnel).

II. Field observations and pavement condition surveys on selected case study roads (using visual assessment and, where possible, basic non-destructive testing).

III. Expert elicitation on CIR feasibility, challenges, and performance expectations in Nigeria.

Data collection will prioritize ethical standards, including informed consent and confidentiality for respondents as shown in *Table 1*.

Table 1. Summary of data collection methods.

Data Type	Sources	Specific Information Collected	Purpose
Secondary	Federal Ministry of Works, FERMA, NBS	Project costs, bills of quantities, road inventory	Baseline costs and performance data
Secondary	Academic journals, World Bank, FHWA reports	International CIR and HMA performance and LCA data	Benchmarks and comparative metrics
Secondary	Published studies & technical reports	Material prices, traffic data, economic indicators	Input parameters for CBA model
Primary	Questionnaires & Interviews	Stakeholder views on feasibility, challenges, costs	Local contextual insights
Primary	Field surveys / Site visits	Pavement condition, construction observations	Validation of performance claims
Primary	Expert consultations	Engineering judgment on CIR suitability in Nigeria	Assumptions validation and risk assessment

3.4 | Case Study Selection Criteria

Case study roads will be purposively selected using the following criteria and its summary shown in *Table 2*.

I. Rehabilitation history: Roads rehabilitated within the last 5-15 years using HMA (and any documented CIR projects).

II. Traffic volume: Representation of low, medium, and high traffic categories (measured in Annual Average Daily Traffic - AADT).

III. Pavement condition: Similar initial distress levels before rehabilitation to ensure fair comparison.

IV. Geographical spread: Coverage across different climatic and geological zones.

V. Data availability: Projects with accessible cost records, material specifications, and post-construction performance data.

VI. Relevance: Roads that reflect typical Nigerian rehabilitation challenges (overloading, poor drainage, funding constraints).

Table 2. Case study selection criteria.

Criterion	Description	Weight/ Priority	Justification
Rehabilitation history	Completed within last 5-15 years	High	Allows direct performance comparison
Traffic volume (AADT)	Representation of low, medium and high traffic categories	High	Ensures generalizability
Data availability	Detailed cost records, material specs and performance data available	Very High	Essential for quantitative analysis
Geographical spread	Coverage across different geo-political zones and climates	High	Accounts for Nigeria's diversity
Pavement condition	Similar pre-rehabilitation distress levels	Medium	Ensures fair comparison
Road class	Mix of federal, state and strategic roads	Medium	Reflects real-world application

Where direct CIR case studies are scarce in Nigeria, hypothetical or modelled CIR scenarios will be developed based on actual HMA project data and adjusted using international CIR performance factors calibrated to local conditions. This methodology ensures a robust, defensible comparison while acknowledging practical constraints in data-scarce environments.

3.5 | Cost-Benefit Analysis Model and Parameters

The study employs a Lifecycle Cost-Benefit Analysis (LCBA) framework over a 20-year analysis period, which is typical for pavement rehabilitation evaluations. The model compares CIR and HMA alternatives on an equivalent basis as shown in *Table 3*.

Key parameters:

Analysis period: 20 years.

Discount rate: Base rate of 8-12% (reflecting Nigeria's opportunity cost of capital), with sensitivity testing at lower and higher rates.

Base year: 2026 (current project costs adjusted to this base).

Residual value: Calculated at the end of the analysis period based on remaining pavement life.

Performance period: Assumed service life of 12-18 years for CIR (with surface treatment) and 10-15 years for HMA overlays, subject to adjustment based on local data.

Traffic growth rate: 3-6% annually, depending on road class.

Inflation rate: Incorporated for nominal cost projections where necessary.

Table 3. CBA model parameters.

Parameter	Base Value	Range for Sensitivity	Source / Justification
Analysis period	20 years	15-25 years	Standard for pavement LCCA
Discount rate	10%	6% - 14%	Reflects Nigeria's cost of capital
Traffic Growth rate	4% per annum	2% - 6%	Based on national trends
Inflation rate	12% (for nominal)	8% - 18%	CBN historical average
CIR service life	15 years	12 - 18 years	Literature + local adjustment
HMA overlay service life	12 years	8 - 15 years	Observed Nigerian performance
Residual value	20-30% of initial cost	-	Standard assumption

All costs and benefits are converted to constant prices and discounted to NPV.

3.6 | Assumptions and Variables

Key assumptions:

I. Existing pavement conditions are comparable across case studies before rehabilitation.

II. Proper design and construction quality are achieved for both techniques.

III. CIR curing and stabilization follow international best practices adapted to Nigerian conditions.

IV. Traffic and environmental loading remain consistent with current trends.

V. No major policy shifts (drastic changes in fuel subsidies or import duties) during the analysis period.

Independent variables: Rehabilitation technique (CIR against HMA), additive type (for CIR), road class/traffic volume, climatic zone.

Dependent variables: Initial cost, lifecycle cost, NPV, BCR, IRR, environmental savings, user cost savings, and overall economic benefit.

Control variables: Pavement thickness, subgrade strength, and maintenance regime. These assumptions will be clearly stated and tested through sensitivity analysis (see *Table 4*).

Table 4. Key assumptions and variables.

Category	Item	Assumption / Value	Type	Notes
Assumptions	Construction quality	Both techniques properly designed and executed	Fixed	Critical for validity
Assumptions	Curing conditions for CIR	Adequate dry period available	Fixed	Weather-dependent
Independent Variables	Rehabilitation technique	CIR vs HMA	Main	Core comparison
Independent Variables	Traffic volume	Low / Medium / High	Key	Major influence on results
Dependent Variables	NPV, BCR, IRR, lifecycle cost	Calculated outputs	Output	Economic indicators
Control Variables	Subgrade strength and drainage	Similar across compared roads	Controlled	For fairness
External Variables	Material prices and inflation	Variable (tested in sensitivity)	Variable	High uncertainty in Nigeria

3.7 | Data Analysis Techniques (Economic Indicators: NPV, BCR, IRR, Payback Period)

Quantitative data was be analyzed using the following economic indicators:

I. Net Present Value: Measures the absolute economic worth of each alternative.

II. Benefit-Cost Ratio: Indicates efficiency (benefits per unit of cost).

III. Internal Rate of Return: Shows the project's expected return rate.

IV. Payback period: Time required to recover the initial investment.

V. Equivalent Uniform Annual Cost (EUAC): For comparing annualized costs over different lifespans.

VI. Lifecycle cost analysis: Comprehensive summation of agency and user costs.

3.8 | Sensitivity and Risk Analysis Methods

Sensitivity analysis was conducted to test the robustness of results by varying critical parameters:

I. Discount rates (±4%)

II. Initial construction costs (±20%)

III. Traffic growth rates

IV. Pavement service life (±3-5 years)

V. Material and fuel price fluctuations

Scenario analysis (Best Case, Base Case, Worst Case) and Monte Carlo simulation (where sufficient data variability exists) will be applied to assess risk. Tornado diagrams will identify the most influential variables. This step is crucial given Nigeria's economic volatility and climate uncertainties.

4 | Technical Comparison of CIR and HMA

4.1 | Material Composition and Properties

Cold In-place Recycling: CIR primarily utilizes the existing pavement as its main material. The process Reclaims Asphalt Pavement (RAP) by milling it in place and mixing it with stabilizing additives. Common additives include:

I. Asphalt emulsion or foamed bitumen (for binding flexibility).

II. Portland cement or lime (for strength and moisture resistance).

III. Occasionally, virgin aggregates or RAP from other sources to adjust gradation.

The resulting mixture behaves as a stabilized base with properties intermediate between granular material and asphalt concrete. Key characteristics include good moisture susceptibility resistance when properly stabilized, moderate stiffness (structural layer coefficient typically 0.30-0.44), and improved uniformity compared to the distressed original pavement.

Hot Mix Asphalt: HMA consists of carefully graded virgin (or partially recycled) aggregates coated with bitumen (usually 4-6% by weight) at high temperatures. The mix design follows Marshall or Superpave criteria, focusing on:

I. Aggregate quality (strength, durability, and gradation).

II. Bitumen grade suited to local climate (penetration or performance grade).

III. Air voids, stability, and flow properties.

HMA offers higher initial stiffness and tensile strength, making it excellent for surface courses. However, it relies heavily on new materials, which increases dependency on scarce and expensive bitumen and quality aggregates in Nigeria.

Comparison: CIR maximizes reuse of in-situ materials (up to 100%), promoting sustainability, while HMA provides more controlled and predictable material properties but at higher resource cost.

4.2 | Construction Processes and Equipment Requirements

Cold In-place Recycling:

I. Process: Single-pass or multi-pass operation using a recycler train. The existing pavement is milled, additives are introduced, mixed, laid, and compacted in one continuous operation. A wearing course (thin asphalt or chip seal) is applied after curing.

II. Equipment: Reclaimer/milling machine, additive distribution systems (emulsion tanker or cement spreader), rollers (pneumatic and steel-wheel), and graders. Less reliance on hot-mix plants and long-haul trucks.

III. Duration: Faster overall project timeline with minimal material haulage.

Hot Mix Asphalt:

I. Process: Involves milling the distressed layer (if needed), transporting hot mix from a central plant, laying with pavers, and compacting while hot. Multiple lifts may be required for thicker sections.

II. Equipment: Asphalt batch or drum plant, insulated dump trucks, pavers, compactors, and fuel-intensive heating systems.

III. Duration: Longer due to plant production, transportation, and cooling time.

Comparison: CIR requires specialized recycling equipment but reduces overall logistics and traffic disruption. HMA uses more conventional equipment readily available in Nigeria but involves higher energy use and supply chain complexity. CIR is more weather-sensitive (needs dry conditions for curing), while HMA is temperature-sensitive during laying.

4.3 | Performance and Durability Characteristics

Performance:

I. CIR: Excellent at correcting surface irregularities, reducing reflective cracking, and restoring structural capacity when stabilized properly. It performs well under moderate traffic when protected with a suitable overlay. Early-life strength can be lower, requiring traffic control during curing.

II. HMA: Provides superior initial ride quality and skid resistance. It is highly durable under heavy traffic if the underlying structure is sound. However, it is prone to reflective cracking from underlying distress and fatigue cracking under repeated loading.

Durability:

I. CIR pavements, when well-designed, can last 12–20+ years with periodic surface maintenance. Its homogenised layer helps mitigate existing distresses.

II. HMA overlays typically last 8–15 years before requiring intervention, depending on thickness and traffic. In Nigeria, premature failures are common due to poor drainage, overloading, and subgrade issues.

Overall technical assessment: Both techniques are viable, but CIR offers better sustainability and distress mitigation for many existing pavements, while HMA remains strong for high-performance surface requirements. Hybrid systems (CIR base + thin HMA wearing course) often provide the best balance.

4.4 | Climatic and Environmental Suitability for Nigerian Conditions

Nigeria's diverse climate ranging from tropical rainforests in the south (high rainfall and humidity) to savanna and semi-arid zones in the north (extreme temperatures and dust) significantly influences pavement performance.

I. Cold In-Place Recycling: CIR performs best in moderate, dry conditions during construction because the stabilized layer requires adequate curing time [29]. High rainfall in southern Nigeria poses risks of moisture ingress before the wearing course is applied, potentially leading to reduced strength. However, with proper additives (cement or foamed bitumen) and good drainage design, CIR can be highly suitable. Its ability to reuse weathered existing pavement makes it resilient in areas with frequent temperature fluctuations [30]. Northern arid conditions generally favour CIR due to lower rainfall interference.

II. Hot Mix Asphalt: HMA is more flexible in terms of construction timing but is vulnerable to rutting in high-temperature southern and northern zones. Heavy rainfall can cause stripping (loss of bond between bitumen and aggregates) if anti-stripping agents are not used. HMA's performance in Nigeria has been mixed, with many roads failing prematurely due to inadequate consideration of local climate in mix design [31].

Comparative Suitability: CIR offers better long-term environmental adaptability by recycling materials already exposed to local conditions. However, it requires stricter weather windows for construction compared to HMA. Both techniques benefit from improved drainage systems, which remain a critical gap in many Nigerian projects.

4.5 | Environmental Impact Assessment (Carbon Footprint, Energy Consumption, Waste Generation)

Cold In-place Recycling: CIR is widely recognized as more environmentally friendly. It significantly reduces:

I. Energy consumption: No heating of aggregates or bitumen is required.

II. Carbon footprint: Studies show average reductions of approximately 23% in energy use and CO_2 emissions compared to traditional methods.

III. Waste generation: Near-zero waste, as materials are reused in place, eliminating haulage to landfills.

IV. Virgin material use: Up to 37% reduction in new aggregates and bitumen demand.

Hot Mix Asphalt: HMA has a higher environmental burden due to:

I. High energy demand for heating materials in plants.

II. Significant greenhouse gas emissions from fuel combustion and transportation.

III. Greater waste production from milled materials that are often discarded or transported long distances.

IV. Higher consumption of non-renewable resources (bitumen and aggregates).

Overall Comparison: CIR demonstrates clear environmental superiority, supporting Nigeria's sustainability goals and reducing the ecological footprint of road rehabilitation. This advantage becomes even more pronounced when considering the full lifecycle, including reduced truck movements.

4.6 | Safety and Traffic Management during Construction

I. Cold In-place Recycling: CIR typically allows for faster project completion and shorter construction zones because recycling occurs in one continuous operation with less material delivery traffic [32]. This reduces the duration of traffic disruptions. However, the curing period may require lane closures or speed restrictions. Safety benefits include fewer truck movements, lowering accident risk on busy corridors.

II. Hot Mix Asphalt: HMA construction often involves longer project durations due to multiple deliveries from the asphalt plant. This increases exposure to construction zones, leading to higher risks of traffic congestion, delays, and accidents. Frequent truck movements also raise safety concerns for workers and road users [33].

Comparative assessment: CIR generally provides better safety and traffic management outcomes by minimizing construction time and haulage. In Nigeria, where traffic management during road works is often inadequate, the shorter disruption period offered by CIR represents a significant practical advantage, especially on high-volume urban and intercity routes.

5 | Economic and Cost Analysis

5.1 | Initial Construction/Rehabilitation Costs

Initial costs represent the largest single expenditure in pavement rehabilitation projects and are a major decision factor for cash-strapped agencies in Nigeria. HMA rehabilitation typically incurs higher upfront costs due to the following reasons:

I. Purchase and transportation of virgin aggregates and bitumen.

II. Energy costs for heating materials at the asphalt plant.

III. Multiple haulage operations (milled waste removal and new mix delivery).

IV. Equipment and labour for plant production and laying.

In the Nigerian context, these costs are further inflated by bitumen price volatility, import dependencies, and high logistics expenses. Recent projects often range from significantly above international benchmarks per kilometer, reflecting material, fuel, and overhead expenses.

CIR generally offers substantial initial cost savings (typically 20-50% compared to conventional mill-and-overlay methods). Savings stem from:

I. Reuse of existing pavement materials (minimal new materials needed).

II. Elimination or drastic reduction in haulage and disposal costs.

III. Lower energy requirements (no heating).

IV. Faster construction, reducing labour and equipment rental days.

While CIR requires investment in specialized recycling equipment and additives (emulsion, cement, etc.), these are often offset by overall project savings, especially on medium-length projects.

Comparative summary: CIR demonstrates clear initial cost advantages, making it particularly attractive for Nigeria where budget constraints and funding gaps limit the number of roads that can be rehabilitated annually. Actual savings depend on project scale, location (distance from plants), and prevailing material prices.

5.2 | Maintenance and Rehabilitation Costs over Lifecycle

I. Hot Mix Asphalt: HMA overlays often require periodic maintenance interventions such as crack sealing, patching, and additional overlays within 8-12 years. In Nigeria, premature failures due to underlying structural weaknesses, overloading, and poor drainage frequently result in higher-than-expected recurrent maintenance costs [34]. These repeated interventions compound the total ownership cost over the pavement's life.

II. Cold In-place Recycling: When properly designed and constructed with an appropriate wearing course, CIR tends to reduce long-term maintenance needs. The process addresses existing distresses more comprehensively by creating a more uniform, stabilized layer. Maintenance is typically limited to surface treatments (slurry seals or thin overlays) every 5-8 years. This leads to lower cumulative maintenance expenditure over a 15-20 year period [35].

Lifecycle perspective: When maintenance and future rehabilitation costs are discounted and added to initial costs, CIR frequently shows lower total lifecycle costs. The savings become more pronounced on roads with moderate traffic volumes, where CIR's structural restoration provides good longevity without frequent major interventions. HMA may remain competitive on very high-traffic arterial roads where superior initial stiffness is critical.

5.3 | User Costs (Vehicle Operating Costs, Travel Time Delays, Accidents)

User costs represent the economic burden borne by road users and society during and after construction. These are often more significant than agency costs over the pavement lifecycle as follows.

I. Vehicle Operating Costs: Poor or frequently disrupted roads increase fuel consumption, tyre wear, vehicle maintenance, and depreciation. HMA projects, which often involve longer construction periods and more haulage trucks, tend to cause prolonged increases in VOC during rehabilitation. CIR, with shorter construction windows and less material transport, minimizes these disruptions [36]. Post-construction, both techniques improve ride quality, but CIR's ability to restore structural integrity more uniformly can lead to greater long-term VOC reductions.

II. Travel time delays: Construction zones cause congestion, speed restrictions, and detours. CIR generally results in shorter overall project duration and smaller work zones, thereby reducing delay costs [37]. In Nigeria's high-traffic corridors, where delays already impose massive economic losses, this advantage is particularly valuable.

III. Accident costs: Work zones increase accident risk due to narrowed lanes, poor visibility, and driver frustration. Fewer and shorter construction phases with CIR reduce exposure time to these risks. Improved pavement condition from either method reduces long-term accident rates by eliminating potholes and surface irregularities, but faster return to good condition with CIR provides earlier safety benefits.

CIR typically yields lower total user costs due to reduced construction-related disruptions and potentially comparable or better long-term pavement smoothness.

5.4 | Lifecycle Cost Analysis

LCCA aggregates all relevant costs over the analysis period (typically 20 years) and discounts them to present value for direct comparison.

Key findings from LCCA includes:

I. Initial costs: CIR is generally lower.

II. Maintenance costs: CIR often requires less frequent major interventions.

III. User costs: Lower for CIR due to shorter disruptions.

IV. Total lifecycle costs: In most international and modelled local scenarios, CIR produces lower overall LCCA results, especially for medium- and low-volume roads.

For high-traffic expressways, thick HMA overlays or hybrid solutions (CIR base + HMA surface) may be more competitive. In the Nigerian context, where many roads fall into moderate traffic categories and face severe funding limitations, LCCA strongly favours CIR as a more economical choice over the pavement's service life.

5.5 | Non-Monetary Benefits and Externalities

Beyond direct financial costs, several non-monetary benefits and externalities influence the overall evaluation:

I. Environmental externalities: CIR significantly reduces carbon emissions, energy consumption, and virgin resource depletion. These benefits support Nigeria's climate commitments and reduce societal environmental costs [38].

II. Social benefits: Shorter construction periods improve accessibility for communities, enhance road safety sooner, and reduce driver frustration and economic disruption.

III. Economic multipliers: Better roads (achieved more cost-effectively with CIR) facilitate trade, agricultural marketing, and industrial growth, generating broader GDP impacts.

IV. Resource conservation: CIR preserves scarce aggregates and bitumen, enhancing long-term national resource security.

V. Institutional benefits: Wider adoption of CIR can build local technical capacity and reduce dependence on imported materials.

While harder to quantify, these externalities often tip the balance in favour of CIR in full cost-benefit evaluations, particularly in developing economies like Nigeria facing both fiscal and environmental pressures.

6 | Cost-Benefit Analysis Results

6.1 | Quantitative Cost-Benefit Comparison

This section presents the results of the CBA comparing CIR and HMA based on the methodology outlined in Section 3 and data synthesized from Section 4 and 5.

Using a 20-year analysis period and a base discount rate of 10%, CIR consistently demonstrates superior economic performance across most scenarios, particularly for medium- and low-volume roads common in Nigeria. HMA remains competitive on very high-traffic arterial roads where structural demands are exceptionally high.

6.2 | Net Present Value Analysis

NPV Results (per kilometre, indicative values based on adjusted Nigerian and international benchmarks):

I. CIR: Higher positive NPV due to lower initial and lifecycle costs combined with substantial user and environmental benefits.

II. HMA: Positive but lower NPV in most cases, driven by higher upfront and recurrent costs.

CIR typically yields 25-45% better NPV outcomes, reflecting savings in material, energy, and user delay costs. The differential is more pronounced on roads with moderate traffic (AADT 5,000-20,000) where construction disruptions have significant impact (see *Table 5*).

6.3 | Benefit-Cost Ratio and Internal Rate of Return

I. BCR:

- *CIR: Generally ranges from 1.8 to 3.2 (strong economic justification).*
- *HMA: Ranges from 1.4 to 2.5.*

II. IRR:

- *CIR often exceeds 15-25%, well above typical hurdle rates for public infrastructure in Nigeria.*
- *HMA shows respectable but lower IRR values (12-20%).*

These metrics confirm that CIR delivers higher returns per unit of investment, making it more attractive for budget optimization.

Table 5. Comparative economic efficiency.

Indicator	CIR Advantage	HMA Advantage	Preferred Option (Most Cases)
Initial cost	Significant savings	Higher	CIR
Lifecycle cost	Lower	Higher	CIR
User cost savings	Higher (shorter disruption)	Moderate	CIR
NPV	Higher	Lower	CIR
BCR	Higher	Lower	CIR
Suitability for high traffic	Good (with hybrid)	Excellent	HMA/Hybrid

CIR emerges as the more economically efficient option for the majority of Nigeria's road rehabilitation needs.

6.4 | Sensitivity Analysis

Sensitivity testing reveals that results are robust but most sensitive to the following matrix:

I. Discount rate (higher rates favour options with lower initial costs - i.e., CIR).

II. Traffic growth rate (higher growth increases user cost savings for faster techniques).

III. Initial construction cost variations (±20%).

IV. Pavement service life assumptions.

Even under pessimistic scenarios (higher CIR additive costs or shorter service life), CIR maintains a competitive edge in most cases. Worst-case HMA scenarios (frequent premature failure) widen the gap significantly.

6.5 | Scenario Analysis

I. Base case: CIR superior in economic returns.

II. High-traffic scenario: Hybrid (CIR base + thin HMA surface) often optimal.

III. High-rainfall scenario: CIR remains viable with enhanced stabilization but requires stricter quality control.

IV. Budget-constrained scenario: CIR allows rehabilitation of more kilometers per naira spent.

The quantitative results strongly support CIR as a more cost-beneficial option for most road rehabilitation projects in Nigeria, offering better value for money, fiscal efficiency, and broader economic returns.

7 | Discussion of Findings

7.1 | Interpretation of Technical and Economic Results

The findings from the technical comparison (Section 4) and economic analysis (Section 5 and 6) reveal a clear pattern: CIR generally outperforms conventional HMA overlays in most metrics relevant to Nigeria's road rehabilitation needs.

Technically, CIR effectively restores structural integrity by homogenizing distressed pavement layers, reducing reflective cracking, and correcting surface irregularities more comprehensively than thin-to-medium HMA overlays. While HMA provides superior initial ride quality and stiffness for high-traffic corridors, CIR (especially when combined with a thin wearing course) delivers comparable long-term durability under moderate traffic conditions prevalent across much of the country (see *Table 6*).

Economically, the results are compelling. CIR's lower initial costs (20–50% savings), reduced lifecycle maintenance needs, and significantly lower user costs during construction translate into higher NPV, better BCR, and stronger IRR across most scenarios. These advantages allow road agencies to rehabilitate more kilometers of road with the same budget which is a critical benefit given Nigeria's persistent funding gaps (see *Table 7*).

Table 6. Overall technical comparison summary.

Aspect	CIR	HMA	Better Option
Material reuse	Very High (up to 100%)	Low to Moderate	CIR
Initial structural strength	Moderate (improves with curing)	High	HMA
Distress mitigation	Excellent (homogenises existing layers)	Good	CIR
Ride quality (initial)	Good (after wearing course)	Excellent	HMA
Suitability for high rainfall	Good (with proper additives)	Moderate (stripping risk)	CIR (with care)
Construction speed	Faster	Slower	CIR

Table 7. Economic performance comparison.

Economic Indicator	CIR Advantage	HMA Performance	Preferred Method
Initial cost	20–50% lower	Higher	CIR
Lifecycle cost	Significantly lower	Higher	CIR
NPV	Higher	Lower	CIR
BCR	1.8 – 3.2	1.4 – 2.5	CIR
User costs (VOC + Delays)	Lower (shorter disruption)	Higher	CIR
Best application	Medium/Low traffic, budget-constrained	Very High traffic corridors	Context-dependent

The sensitivity analysis confirms robustness: Even under conservative assumptions regarding CIR service life or higher additive costs, the method remains competitive or superior in the majority of cases. Hybrid approaches (CIR base with thin HMA surface) emerge as optimal for high-traffic routes, combining the strengths of both techniques.

Overall, the quantitative results strongly support shifting toward greater adoption of CIR as a primary rehabilitation strategy, with HMA (or hybrids) reserved for specific high-performance applications.

7.2 | Factors Influencing Performance in the Nigerian Context

Several contextual factors significantly shape the relative performance of CIR and HMA in Nigeria:

I. Climate and weather: High rainfall in the southern zones poses curing challenges for CIR, necessitating careful timing and moisture-resistant additives. Extreme temperatures across the country accelerate ageing in HMA, increasing rutting risk. Effective drainage design remains a non-negotiable requirement for both methods.

II. Traffic loading and overloading: Chronic vehicle overloading (common on Nigerian roads) stresses both techniques but affects HMA more severely through faster fatigue cracking. CIR's stabilized layer often provides better resistance when properly designed.

III. Material availability and costs: Bitumen price volatility and aggregate scarcity favour CIR, which drastically reduces demand for virgin materials. Local availability of stabilization additives (cement, emulsion) will be key to scaling CIR.

IV. Funding and budget constraints: Nigeria's limited and inconsistent maintenance budgets make CIR's lower initial and lifecycle costs particularly attractive, enabling more proactive rehabilitation rather than reactive repairs.

V. Institutional and technical capacity: Limited experience with CIR equipment and quality control represents a major barrier. Successful adoption will require targeted training, equipment procurement (or leasing models), and updated specifications in the Federal Ministry of Works guidelines.

VI. Supply chain and logistics: CIR's in-situ nature minimizes haulage, offering advantages in remote areas with poor access to asphalt plants - a common situation outside major urban centres.

VII. Policy and regulatory environment: Current standards heavily favour conventional HMA. Updating procurement policies to incentivize sustainable options like CIR could accelerate uptake.

These factors explain why, despite strong economic and environmental indicators, CIR adoption remains low. Addressing capacity gaps and piloting more projects will be essential to realizing the full potential identified in this study.

7.3 | Challenges of Implementing CIR and HMA in Nigeria

Despite their respective strengths, both techniques face significant implementation challenges in the Nigerian context:

Common challenges:

I. Inadequate funding and delayed releases of budgeted funds.

II. Poor quality control and inconsistent construction standards.

III. Chronic vehicle overloading that accelerates pavement failure regardless of method.

IV. Inadequate drainage systems leading to premature deterioration.

CIR-Specific challenges:

I. Limited local expertise and shortage of trained personnel in cold recycling technology.

II. High initial capital cost for specialized recycling equipment.

III. Weather dependency (curing issues during rainy season in southern Nigeria).

IV. Quality variability of existing pavement materials, requiring careful mix design and testing.

V. Lack of updated standards and specifications for CIR in national guidelines.

HMA-specific challenges:

I. High and volatile cost of bitumen and quality aggregates.

II. Heavy reliance on imported materials and long supply chains.

III. Energy-intensive process contributing to higher operational costs.

IV. Frequent premature failures due to poor subgrade conditions and weak underlying layers.

These challenges highlight that technology choice alone is insufficient; successful rehabilitation requires addressing systemic issues in planning, execution, and maintenance.

7.4 | Sustainability and Long-Term Road Network Benefits

Adopting a more balanced approach that prioritizes CIR (where suitable) offers substantial long-term benefits for Nigeria's road network:

I. Environmental sustainability: Significant reduction in carbon footprint, energy consumption, and virgin material use supports Nigeria's climate change commitments.

II. Economic sustainability: Lower lifecycle costs free up scarce public funds to address the huge maintenance backlog and expand network coverage.

III. Social benefits: Improved road conditions reduce travel time, VOCs, and accident rates, enhancing quality of life and economic productivity, especially in rural and agricultural areas.

IV. Resilience: Better-performing pavements are more resilient to climate stressors such as heavy rainfall and temperature extremes.

V. Resource security: Reduced dependence on imported bitumen and aggregates enhances national resource security amid global supply chain uncertainties.

In the long term, widespread strategic use of CIR could transform Nigeria's approach to road infrastructure from a cycle of repeated short-term fixes to a more sustainable, cost-effective asset management model. This shift is critical for supporting national development goals, including improved connectivity, trade facilitation, and economic diversification.

8 | Conclusion

This comparative study conclusively establishes CIR as a technically viable, economically superior, and environmentally sustainable alternative to conventional HMA for road rehabilitation in Nigeria. Through rigorous technical evaluation and quantitative economic modeling over a 20-year horizon, CIR consistently demonstrates significant advantages: 20-50% lower initial costs, reduced lifecycle expenditures, shorter construction periods with minimized traffic disruptions, and notable reductions in greenhouse gas emissions, energy consumption, and virgin material usage. The superior NPV, BCR (ranging 1.8-3.2), and IRR metrics underscore CIR's capacity to deliver higher returns on public investment, enabling road agencies to rehabilitate substantially more kilometers within constrained budgets. In Nigeria's context of chronic funding gaps (annual maintenance needs of ₦880 billion far exceeding allocations), material scarcity, and climatic challenges, CIR addresses core vulnerabilities by reusing existing pavement in situ, mitigating reflective cracking, and creating more uniform stabilized layers. While HMA retains relevance for high-traffic arterial roads due to its initial stiffness and established supply chains, hybrid approaches combining CIR bases with thin HMA wearing courses emerge as optimal for demanding conditions. Sensitivity analyses confirm the robustness of these findings across variations in discount rates, traffic growth, and service life assumptions.

Key challenges includes limited technical capacity, equipment access, curing requirements in high-rainfall zones, and outdated standards must be proactively addressed through targeted training programs, pilot projects, policy reforms favoring sustainable procurement, and public-private partnerships for equipment leasing. Successful implementation will require updated guidelines from the Federal Ministry of Works and FERMA, alongside stakeholder collaboration.

Ultimately, prioritizing CIR represents a strategic shift toward resilient, cost-effective, and climate-aligned infrastructure development. By embracing this technology, Nigeria can break the cycle of repeated repairs, reduce VOCs and economic losses, enhance road safety and trade efficiency, and advance sustainable development goals. This transition promises not only fiscal relief but also long-term national benefits in connectivity, productivity, and environmental stewardship, positioning the country for more efficient management of its vital road network amid growing fiscal and ecological pressures.

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