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Sustainable and Low-Carbon Construction Materials for Future Infrastructure an Integrated Performance, Durability, Carbon and Life-Cycle Cost Assessment Framework

***Monpara Jayesh Rameshbhai* *[1]**

Coventry University, United Kingdom

Email: jmonpara181@gmail.com

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ABSTRACT

The construction sector is facing increasing pressure to reduce embodied carbon, resource consumption and construction waste while maintaining the structural performance, durability and economic viability of infrastructure. This research investigates sustainable and low-carbon construction materials as alternatives to conventional cementitious and aggregate-based materials, with particular emphasis on supplementary cementitious materials, recycled aggregates and waste-derived construction materials. The study proposes an integrated Performance–Durability–Carbon–Life-Cycle Cost (PDCLC) assessment framework for evaluating sustainable material alternatives for future infrastructure. The proposed methodology combines material characterisation, mechanical performance assessment, durability evaluation, embodied carbon analysis and life-cycle cost assessment. Key engineering indicators, including compressive strength, tensile and flexural performance, water absorption, durability behaviour, embodied CO_2 emissions and whole-life cost, are evaluated to establish the relationship between material composition, engineering performance and sustainability outcomes. A multi-criteria assessment approach is then proposed to identify material solutions that provide an appropriate balance between structural performance, durability, carbon reduction and economic feasibility. The research aims to address an important limitation in existing sustainable-material studies, where environmental performance, engineering performance and economic implications are frequently assessed independently. By integrating these dimensions within a single decision-support framework, the study provides a systematic approach for selecting low-carbon materials according to infrastructure requirements and life-cycle performance. The proposed framework can support the development of resource-efficient buildings, roads, bridges, precast systems and modular infrastructure while promoting construction-waste utilization and circular material practices. The research contributes to the advancement of sustainable civil engineering by providing a practical performance–carbon–cost-based methodology for low-carbon material selection. The outcomes are intended to support engineers, construction professionals, project managers and infrastructure decision-makers in reducing environmental impacts while maintaining technical and economic performance. The study therefore contributes to the wider development of resilient, resource-efficient and low-carbon infrastructure and establishes a coherent research direction at the intersection of civil engineering, sustainable construction, material innovation and construction cost management.

INTRODUCTION

1.1 Background of Sustainable Construction

Rapid urbanization, population growth and infrastructure development have increased the demand for construction materials. However, conventional construction relies heavily on energy-intensive materials and virgin resources, resulting in significant carbon emissions, resource consumption and waste generation. This has increased the need for resource-efficient and low-carbon construction practices [1][2].

Sustainable construction promotes the use of supplementary cementitious materials (SCMs), recycled aggregates, waste-derived materials and alternative binders to reduce dependence on conventional materials. These approaches can support lower embodied carbon, material circularity and improved resource efficiency [1][2][4].

However, environmental performance alone is insufficient for material selection. Sustainable alternatives must also provide adequate mechanical performance, durability and economic feasibility. Therefore, this study evaluates materials through an integrated approach:

Performance + Durability + Embodied Carbon + Life-Cycle Cost

This provides the basis for selecting sustainable materials for technically reliable and economically viable future infrastructure.

1.2 Global Infrastructure Development and Material Demand

Global infrastructure development continues to increase due to urbanization, population growth, economic development and the modernization of ageing infrastructure. Expansion of buildings, roads, bridges, railways, energy systems and water infrastructure consequently increase the demand for cement, concrete, aggregates and other construction materials. This growing demand places increasing pressure on natural resources and reinforces the need for resource-efficient construction practices [1][2].

Conventional infrastructure remains highly dependent on virgin aggregates and carbon-intensive cementitious materials. Sustainable alternatives such as SCMs, recycled aggregates, waste-derived materials and low-carbon binders can reduce virgin-resource consumption and contribute to lower environmental impacts [1][4][5].

Future infrastructure development therefore requires a transition toward resource-efficient and low-carbon material selection while maintaining the required engineering performance and durability [1][2].

Infrastructure Growth → Material Demand → Resource Pressure → Low-Carbon Material Transition

1.3 Environmental Impact of Conventional Construction Materials

Conventional construction materials such as cement, concrete, steel and natural aggregates have substantial environmental impacts due to energy-intensive production, raw-material extraction and large-scale consumption. Cement manufacturing is particularly carbon-intensive because emissions arise from both limestone calcination and high-temperature clinker production [1][2][3].

The extraction of sand, gravel and other virgin materials contributes to resource depletion and ecosystem pressure, while construction and demolition activities generate large waste streams. Greater use of recycled aggregates and recovered materials can reduce virgin-resource demand and support circular construction practices [4][5].

Therefore, the environmental impact of construction materials should be considered from a life-cycle perspective, including material production, transportation, construction, maintenance and end-of-life stages. Sustainable material selection should reduce environmental impacts without compromising engineering performance or durability [2][5].

Resource Extraction → Material Production → Construction → Use/Maintenance → End-of-Life

Figure 1: Environmental Impact Pathway of Conventional Construction Materials

1.4 Carbon Emissions from Cement and Concrete

Cement and concrete are major contributors to the embodied carbon of infrastructure because of their extensive use and the carbon-intensive production of Portland cement. Cement-related emissions arise primarily from limestone calcination during clinker production and the energy required for high-temperature kiln operations [1][2][3].

Reducing clinker content through SCMs, low-clinker cements and alternative binders, together with improved material efficiency and optimized concrete mixtures, provides important pathways for reducing cement-related emissions [1–3]. Recycled aggregates can further improve resource efficiency by reducing dependence on virgin aggregate production [4][5].

However, carbon reduction should be evaluated together with strength, durability and service-life performance. A material with lower initial embodied carbon may not provide the best whole-life solution if inadequate durability results in frequent maintenance or replacement [2]. Therefore, carbon assessment forms one component of the integrated PDCLC framework proposed in this study.

Lower Clinker Content + SCMs/Alternative Binders + Material Efficiency → Lower Embodied Carbon

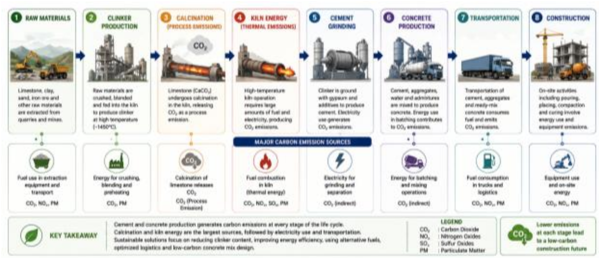


Figure 2: Carbon Emission Pathways in Cement and Concrete Production

1.5 Need for Sustainable and Low-Carbon Materials

The growing environmental impact of conventional construction has increased the need for sustainable and low-carbon materials that reduce embodied carbon, conserve natural resources and minimize construction waste. Material strategies based on lower clinker content, recycled resources and waste utilization can significantly improve the environmental performance of infrastructure [1][2].

Promising approaches include supplementary cementitious materials (SCMs), recycled aggregates, industrial and agricultural by-products, and alternative low-carbon binders. These materials can reduce dependence on virgin resources and conventional Portland cement while supporting circular construction practices [1][4][5].

However, low-carbon materials must provide more than environmental benefits. Their practical adoption depends on achieving acceptable strength, durability, service life, availability and life-cycle cost. Therefore, future material selection should balance engineering performance with environmental and economic objectives rather than focusing only on initial carbon reduction [2][4].

Low Carbon + Resource Efficiency + Engineering Performance + Economic Viability → Sustainable Infrastructure

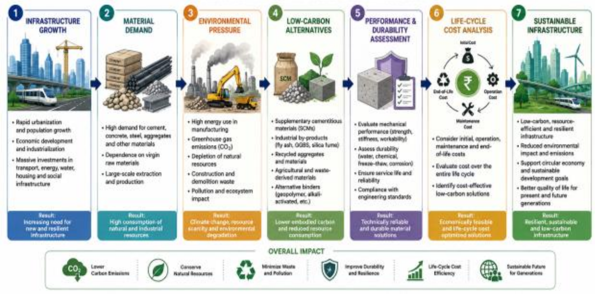


Figure 3: Need for Sustainable and Low-Carbon Materials

1.6 Role of Recycled and Waste-Derived Materials

Recycled and waste-derived materials play an important role in sustainable construction by reducing the consumption of virgin raw materials and diverting construction, industrial and agricultural wastes from disposal. Recycled concrete aggregates, crushed masonry, glass waste and other recovered materials can partially replace conventional aggregates, while industrial and agricultural by-products can be incorporated into cementitious systems [4][5].

The use of these materials supports a circular economy by converting waste streams into secondary construction resources. In addition to reducing waste disposal and natural-resource extraction, appropriate material substitution can contribute to lower embodied environmental impacts and more resource-efficient infrastructure [4][5].

However, recycled and waste-derived materials may exhibit variability in composition, quality, strength and durability. Their successful application therefore requires appropriate material characterization, replacement-level optimization and performance verification to ensure compliance with engineering requirements [4].

Waste Generation → Recovery and Processing → Material Reuse → Reduced Virgin Resources → Circular Construction

Figure 4: Circular Construction Material Flow

1.7 Research Problem

Despite increasing research on sustainable construction materials, their practical selection remains challenging because most studies evaluate mechanical performance, durability, embodied carbon or economic performance separately. A material with low embodied carbon may not necessarily provide adequate durability or whole-life economic benefits, while a high-performance material may have greater environmental impacts [1][2].

Furthermore, recycled aggregates, waste-derived materials and alternative binders can exhibit variations in material properties, long-term performance and cost, making direct comparison difficult [4][5].

A consistent approach is therefore required to assess sustainable materials across multiple technical, environmental and economic criteria.

The key research problem addressed in this study is the lack of an integrated material-selection framework that simultaneously evaluates:

Performance + Durability + Embodied Carbon + Life-Cycle Cost

Accordingly, this study develops the Performance–Durability–Carbon–Life-Cycle Cost (PDCLC) framework to support systematic comparison and selection of sustainable construction materials for future infrastructure.

1.8 Research Aim and Objectives

Research Aim

The aim of this study is to develop an integrated Performance–Durability–Carbon–Life-Cycle Cost (PDCLC) framework for evaluating and selecting sustainable and low-carbon construction materials for future infrastructure.

Research Objectives

The specific objectives are:

- To evaluate the mechanical performance and durability of conventional and sustainable construction material systems.
- To assess the embodied carbon associated with different material alternatives.

- To evaluate the life-cycle cost and economic feasibility of sustainable material systems.
- To compare conventional concrete with SCM-based, recycled aggregate, waste-derived and alternative binder concrete.
- To integrate performance, durability, carbon and cost indicators into a Sustainability Index (SI) for systematic material comparison and selection.
- To identify suitable material strategies for low-carbon and resource-efficient future infrastructure.

LITERATURE REVIEW:

2.1 Conventional Construction Materials

Conventional construction materials, particularly Portland cement concrete, steel, natural aggregates and masonry products, remain fundamental to buildings and infrastructure because of their established mechanical performance, availability and compatibility with existing construction practices. Among these materials, concrete is extensively used because it combines structural versatility, durability and relatively economical production [1][2][6].

However, conventional concrete depends heavily on Portland cement and virgin aggregates. Cement production represents the dominant environmental burden of concrete due to clinker calcination and energy-intensive manufacturing, while large-scale extraction of natural aggregates contributes to depletion of primary resources. Consequently, conventional concrete is associated with substantial embodied carbon and resource consumption across its material-production life cycle [1][2][9][14].

Research has therefore increasingly investigated cement replacement, recycled aggregates and alternative material systems to reduce these impacts. Nevertheless, comparisons between conventional and sustainable concrete should account for differences in mechanical performance and durability, because environmental advantages may vary with mix design, functional unit, transportation and service performance [8][14][31].

In this study, Conventional Concrete (CC) is therefore adopted as the reference material system for comparison with SCM-based concrete (SCM), recycled aggregate concrete (RAC), waste-derived concrete (WDC) and alternative binder concrete (ABC) under the proposed PDCLC framework.

2.2 Environmental Impacts of Conventional Materials

Conventional construction materials generate environmental impacts throughout their life cycle, beginning with raw-material extraction and processing and continuing through manufacturing, transportation, construction and end-of-life management. Cement, concrete and steel are particularly important because their large-scale use contributes substantially to embodied energy, greenhouse-gas emissions and depletion of natural resources [2][6][10].

For cement-based materials, major impacts originate from clinker production, limestone calcination and fuel consumption, whereas steel production involves energy- and carbon-intensive ironmaking and manufacturing processes [2][10][11]. Extraction of natural sand, gravel and other virgin materials further increases resource pressure, while construction and demolition activities generate significant waste streams [5][8].

Life-Cycle Assessment (LCA) studies demonstrate that environmental performance depends not only on material production but also on transportation, service life, maintenance, recycling and end-of-life scenarios. Consequently, evaluating construction materials across consistent life-cycle boundaries is important for identifying genuinely sustainable alternatives [8][12][13].

These environmental limitations provide the basis for replacing or partially substituting conventional materials with SCMs, recycled aggregates, waste-derived resources and alternative low-carbon binders, provided that required engineering performance and durability are maintained [1][2][8].

2.3 Sustainable Construction Materials

Sustainable construction materials are developed to reduce the environmental impacts associated with conventional construction while maintaining the mechanical performance, durability and functionality required for infrastructure. Major approaches include the use of supplementary cementitious materials (SCMs), recycled aggregates, waste-derived materials and alternative low-carbon binders, which can reduce Portland cement consumption, virgin-resource extraction and waste disposal [1][19][20][23]. Recent reviews continue to identify these material pathways as central to low-carbon concrete development.

SCMs such as fly ash, ground-granulated blast-furnace slag (GGBS), silica fume, metakaolin and calcined clay can partially replace Portland cement and reduce clinker demand while maintaining or improving selected engineering properties when appropriately proportioned [1][19][22]. Recycled aggregates obtained from construction and demolition waste further support resource conservation and circular material use, although their influence on strength, water absorption and durability depend strongly on aggregate quality and replacement level [4][8][23].

Alternative binder systems, including alkali-activated materials and geopolymer concrete, provide another pathway for reducing dependence on conventional Portland cement. Research indicates considerable potential for structural and durability applications, although challenges associated with precursor variability, activator requirements, curing conditions, standardization and large-scale implementation remain [15,16,18,24].

Overall, no single sustainable material provides optimum performance under every criterion. Material selection should therefore consider engineering performance, durability, embodied carbon, resource efficiency and life-cycle economic implications simultaneously, providing the basis for the integrated PDCLC assessment adopted in this study [2,8,24].

Figure 5: Classification of Sustainable and Low-Carbon Construction Materials

2.4 Low-Carbon Concrete and Sustainable Infrastructure

Low-carbon concrete is increasingly recognized as an important strategy for reducing the environmental impact of infrastructure while maintaining required structural performance. Its development primarily focuses on reducing Portland clinker content, incorporating supplementary cementitious materials (SCMs), using recycled materials and adopting alternative binder systems [1][2][19][24]. Recent literature confirms that clinker reduction and SCM-based systems remain among the most practical pathways for lowering concrete's embodied carbon.

Common low-carbon approaches include fly ash, GGBS, silica fume, metakaolin, calcined clay/LC³, recycled aggregates, and alkali-activated or geopolymer binders. These strategies can reduce dependence on conventional cement and virgin resources; however, their performance depends strongly on material characteristics, replacement level, mixture design and curing conditions [15][18][19][21][24].

For sustainable infrastructure, carbon reduction alone is insufficient. Low-carbon concrete must also demonstrate adequate strength, durability, service life, constructability and economic feasibility. Recent reviews particularly highlight long-term durability, material variability, field validation and standardization as important barriers to wider infrastructure adoption. [2][19][24][31]

Therefore, the selection of low-carbon concrete should be based on an integrated assessment of engineering performance, durability, embodied carbon and life-cycle cost, rather than carbon reduction alone. This principle directly supports the PDCLC framework developed in this study.

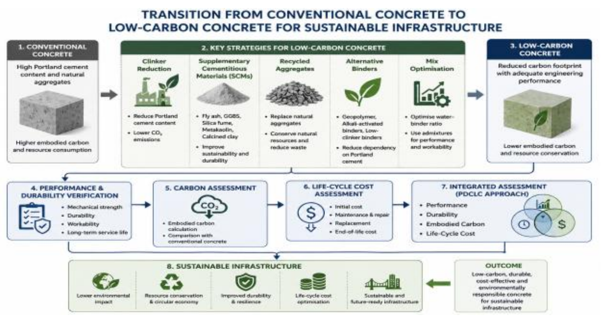


Figure 6: Transition from Conventional Concrete to Low-Carbon Concrete for Sustainable Infrastructure

2.5 Circular Economy in Construction

2.5.1 Circular Material Management

The circular economy (CE) provides an alternative to the traditional "take–make–dispose" model by maintaining materials and components at their highest possible value through reduction, reuse, recovery and recycling. In construction, CE strategies can reduce virgin-resource extraction and construction and demolition waste while extending the useful life of materials and components [25][26][27].

At the material level, circular construction promotes the recovery and reuse of concrete, aggregates, masonry, metals and other construction and demolition materials, together with the utilization of industrial and agricultural by-products as secondary resources. Recycled aggregates and waste-derived materials can therefore contribute to both waste valorization and reduced demand for primary construction resources [4][5][25][28].

However, effective circularity extends beyond recycling. Literature increasingly emphasizes design for durability, adaptability, reuse and disassembly, together with material recovery and life-cycle assessment. Practical implementation is still constrained by material-quality variability, limited standardization, economic uncertainty and insufficient integration of circular principles across the construction value chain [26][27][28][29].

Accordingly, circular material strategies should be evaluated together with engineering performance, durability, environmental impact and life-cycle cost. This integrated perspective supports the PDCLC framework adopted in the present study.

Figure 7: Circular Construction Material Life Cycle for Sustainable Infrastructure

2.6 Existing Research and Research Gap

Existing research has extensively investigated low-carbon cementitious materials, supplementary cementitious materials (SCMs), recycled aggregate concrete, waste-derived materials and alternative binders. Previous studies have demonstrated that these approaches can reduce clinker consumption, virgin-resource demand and embodied carbon while providing acceptable engineering performance under suitable mix-design and curing conditions [1,4,15,18,19,23].

A substantial body of research has also evaluated these materials from individual perspectives such as mechanical strength, durability, environmental impact or life-cycle assessment. For example, recycled aggregate studies frequently focus on strength and environmental benefits [4,8,14], while geopolymer and alternative-binder studies commonly examine carbon reduction, mechanical properties and production requirements [15,16,18]. Circular-economy literature similarly emphasizes waste recovery, recycling and resource efficiency [25–29].

However, the literature remains comparatively fragmented because technical, durability, carbon and economic indicators are often assessed independently. Differences in material characteristics, replacement levels, functional units, system boundaries and service-life assumptions also make direct comparison between sustainable material systems difficult [2,8,14,24]. Furthermore, limited long-term field validation, material variability and standardization continue to restrict large-scale implementation of several emerging material technologies [19,24,29].

Therefore, a key research gap is the absence of a consistent multi-criteria framework capable of comparing different sustainable construction material systems using engineering, durability, environmental and economic criteria simultaneously. To address this gap, the present study develops the Performance–Durability–Carbon–Life-Cycle Cost (PDCLC) framework, in which material alternatives are evaluated through a common Sustainability Index (SI).

Existing Studies → Separate Assessments → Limited Comparability → Integrated PDCLC Framework

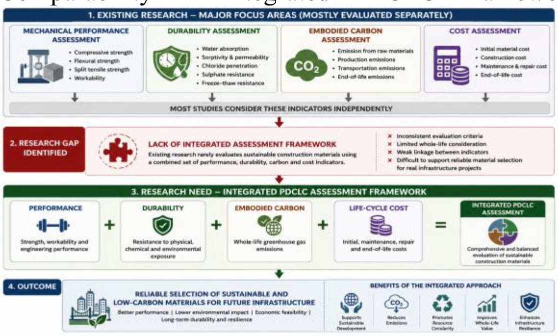


Figure 8: Existing Research Limitations and Identified Research Gap

SUSTAINABLE AND LOW-CARBON MATERIAL SYSTEMS:

3.1 Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) are widely used to reduce the environmental impact of concrete by partially replacing Portland cement and lowering clinker demand. Common SCMs include fly ash, ground-granulated blast-furnace slag (GGBS), silica fume, metakaolin and calcined clay. Their incorporation can reduce embodied carbon while improving resource efficiency through the utilization of industrial by-products and alternative mineral resources [1][19][21][22].

SCMs influence concrete performance through pozzolanic and/or latent hydraulic reactions, which can refine the pore structure and improve selected long-term properties. Depending on SCM type, replacement level and curing conditions, appropriately designed SCM-based concrete can provide satisfactory strength and enhanced resistance to several durability-related deterioration mechanisms [1][13][19][21].

However, SCM performance is affected by chemical composition, fineness, replacement ratio, curing and material availability. High replacement levels may also influence early-age strength development. Therefore, SCM selection and dosage should be optimized by considering both engineering requirements and environmental benefits rather than maximizing cement replacement alone [1][19][22].

Within the present study, SCM-Based Concrete (SCM) is evaluated as one of the principal low-carbon material systems under the PDCLC framework, considering its performance, durability, embodied carbon and life-cycle cost.

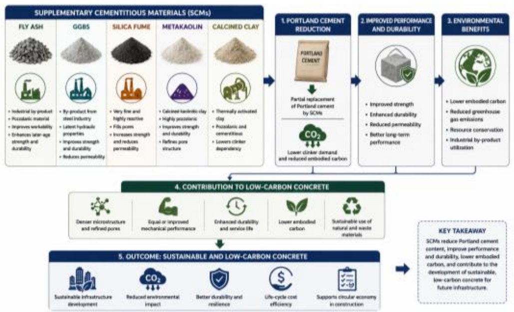


Figure 9: Role of Supplementary Cementitious Materials in Low-Carbon Concrete

3.2 Recycled and Waste-Derived Materials

Recycled and waste-derived materials provide an important pathway for reducing the consumption of virgin construction resources and diverting waste from landfills. Recycled concrete aggregate (RCA), crushed masonry, waste glass and other construction and demolition materials can partially replace natural aggregates, while industrial and agricultural residues can be incorporated as secondary constituents in concrete [4][5][23][30].

The use of recycled aggregates supports resource conservation and circular construction, although residual mortar and higher porosity may increase water absorption and influence the mechanical and durability performance of concrete. Consequently, the performance of recycled aggregate concrete depends strongly on aggregate quality, replacement level, mix design and processing method [4][8][14][23].

Waste-derived materials such as ceramic waste, glass powder, rice husk ash and sugarcane bagasse ash can also be utilized as aggregate replacements or supplementary cementitious components. When appropriately processed and proportioned, these materials can reduce waste disposal and primary-material consumption while providing acceptable engineering performance [20][22][23][30][32].

However, variability in waste composition and processing can affect consistency and long-term performance. Therefore, recycled and waste-derived materials require appropriate characterization, quality control and performance validation before large-scale structural application [4,23,30]. In this study, Recycled Aggregate Concrete (RAC) and Waste-Derived Concrete (WDC) are evaluated separately within the PDCLC framework.

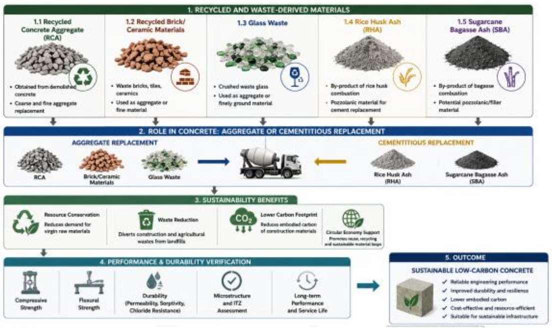


Figure 10: Integration of Recycled and Waste-Derived Materials into Sustainable Concrete

3.3 Alternative Low-Carbon Binders

Alternative low-carbon binders offer a potential route for reducing dependence on ordinary Portland cement (OPC) and the associated emissions from clinker production. Important systems include alkali-activated materials, geopolymers and other low-clinker binders, which can utilize aluminosilicate-rich precursors such as fly ash, slag and metakaolin [15][16][18][24].

Alkali-activated and geopolymer systems can achieve suitable mechanical strength and durability when precursor composition, activator concentration and curing conditions are appropriately controlled. Their environmental performance can also be favorable compared with conventional OPC systems, although the magnitude of carbon reduction depends on precursor sourcing, activator production, transportation and mixture design [15][16][18].

Despite their potential, large-scale implementation remains constrained by material variability, activator-related impacts, curing requirements, cost, availability and limited standardization. Therefore, alternative binders should be assessed using both technical and life-cycle criteria rather than assuming that every non-OPC binder automatically provides a lower-carbon solution [16][18][24].

In this study, Alternative Binder Concrete (ABC) is included as a distinct material system and evaluated together with conventional and other sustainable concretes using the proposed PDCLC framework.

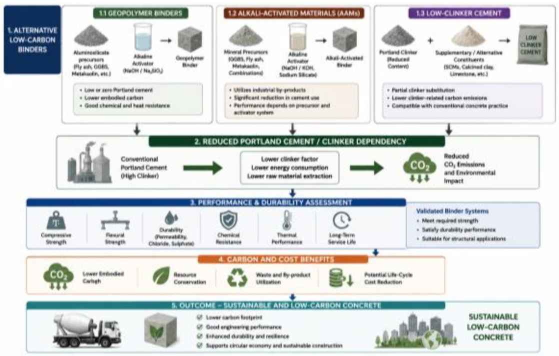


Figure 11: Alternative Low-Carbon Binder Pathways for Sustainable Concrete

3.4 Material Selection and Mix Composition

Material selection and mix composition are critical for developing sustainable concrete because the environmental benefits of alternative materials must be achieved without compromising strength, durability, workability and long-term performance. The selection process therefore considers material properties, replacement level, compatibility, availability and environmental impact.

3.4 Material Selection and Mix Composition

Material selection and mix composition are critical to achieving an appropriate balance between engineering performance, durability and environmental benefits. The sustainable concrete systems considered in this study include Conventional Concrete (CC), SCM-Based Concrete (SCM), Recycled Aggregate Concrete (RAC), Waste-Derived Concrete (WDC), and Alternative Binder Concrete (ABC). The characteristics of each system depend on binder type, replacement level, aggregate quality, water-to-binder ratio and curing conditions [1][4][18][21].

For SCM-based systems, the replacement level should provide adequate cement reduction without compromising required strength and durability. In RAC and WDC, the proportion and quality of recycled or waste-derived constituents must be controlled because variations in porosity, water absorption and material composition can affect concrete performance [4][23][30]. Alternative binder systems similarly require appropriate selection of precursor materials, activators and curing conditions [16][18].

Accordingly, mix composition should not be selected solely to maximize waste utilization or carbon reduction. It should provide the required structural performance and durability while minimizing embodied carbon and life-cycle cost. This multi-criteria principle provides the basis for subsequent evaluation under the PDCLC framework [1][2][8].

Table 1. Material Systems Considered

Code	Material System	Main Material Strategy
CC	Conventional Concrete	OPC + natural aggregates
SCM	SCM-Based Concrete	Partial cement replacement with SCMs
RAC	Recycled Aggregate Concrete	Partial replacement of natural aggregates with RCA
WDC	Waste-Derived Concrete	Incorporation of processed waste-derived constituents
ABC	Alternative Binder Concrete	Reduced/alternative OPC binder system

3.5 Expected Environmental and Engineering Benefits

The sustainable material systems considered in this study are expected to provide combined environmental and engineering benefits compared with conventional material-intensive construction. SCMs and alternative binders can reduce Portland cement and clinker demand, while recycled and waste-derived materials can decrease the consumption of virgin resources and support the beneficial utilization of waste streams [1][4][15][23].

From an environmental perspective, these strategies can contribute to lower embodied carbon, reduced raw-material extraction, waste diversion and improved material circularity. However, the magnitude of these benefits depends on factors such as replacement level, processing requirements, transportation distance and material source [2][5][8][16].

From an engineering perspective, appropriately designed sustainable concrete can achieve satisfactory strength, durability and service-life performance. SCMs and alternative binders may improve selected durability characteristics, whereas recycled and waste-derived materials require careful quality control and mix optimization to manage variations in porosity, water absorption and material properties [4][18][21][23].

Therefore, sustainable material systems should be evaluated through a balanced multi-criteria approach, rather than environmental performance alone. The PDCLC framework adopted in this study integrates these benefits with embodied carbon and life-cycle cost to support practical material selection.

RESEARCH METHODOLOGY:

4.1 Overall Research Framework

This study adopts an integrated methodology for evaluating sustainable and low-carbon construction materials based on four principal dimensions: mechanical performance (P), durability (D), embodied carbon (C), and life-cycle cost (L). Five material systems are considered: Conventional Concrete (CC), SCM-Based Concrete (SCM), Recycled Aggregate Concrete (RAC), Waste-Derived Concrete (WDC), and Alternative Binder Concrete (ABC).

The methodology consists of material characterization, mechanical performance assessment, durability evaluation, embodied-carbon assessment and life-cycle cost analysis. The resulting indicators are normalised to enable comparison between parameters having different units and scales. The normalised indicators are subsequently integrated through the proposed Performance–Durability–Carbon–Life-Cycle Cost (PDCLC) framework.

he overall assessment sequence is:

Material Selection → Characterization → Performance → Durability → Carbon → Life-Cycle Cost → PDCLC Evaluation

For the final multi-criteria assessment, the Sustainability Index (SI) is expressed as:

$$SI = \omega_P P_N + \omega_D D_N + \omega_C C_N + \omega_L L_N \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

subject to:

$$\omega_P + \omega_D + \omega_C + \omega_L = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where:

P_N = normalized mechanical performance indicator

D_N = normalized durability indicator

C_N= normalized embodied-carbon indicator

L_N = normalized life-cycle cost indicator

$\omega_P, \omega_D, \omega_C, \omega_L$ = corresponding weighting factors

For performance and durability, higher normalized values indicate better performance, whereas the normalization direction for embodied carbon and life-cycle cost is reversed, because lower carbon and lower cost represent preferable outcomes.

The resulting SI provides a common basis for comparing the five material systems and identifying alternatives that achieve a balanced combination of engineering reliability, durability, carbon reduction and economic feasibility.

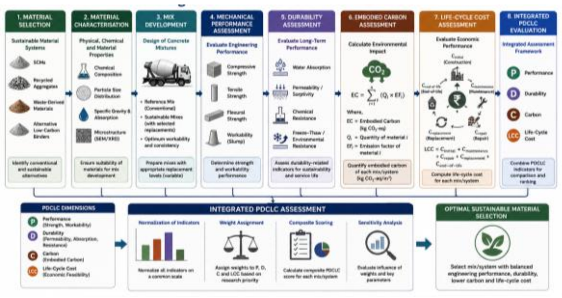


Figure 12: Overall Research Methodology and Integrated PDCLC Assessment Framework

4.2 Material Characterization

Material characterization is conducted to establish the physical and chemical properties of the constituent materials before evaluating their mechanical, durability and environmental performance. The principal materials considered include cementitious binders, SCMs, natural and recycled aggregates, waste-derived constituents and precursors used in alternative binder systems.

For binder materials, relevant characteristics include chemical composition, particle size/fineness and specific gravity, while aggregate characterization includes particle-size distribution, specific gravity and water absorption. For recycled and waste-derived materials, particular attention is given to porosity, moisture absorption and material variability, as these properties can influence workability, strength and durability. Recycled aggregates commonly exhibit higher water absorption because of adhered mortar and increased porosity compared with natural aggregates [4].

The characterization results provide the basis for selecting appropriate material proportions and interpreting subsequent performance differences among CC, SCM, RAC, WDC and ABC systems. Only properties relevant to the selected material system and subsequent PDCLC assessment are considered to avoid unnecessary testing.

Table 2. Key Characterization Parameters

Material Category	Important Parameters
Cement / SCMs	Chemical composition, fineness, specific gravity
Natural Aggregates	Gradation, specific gravity, water absorption
Recycled Aggregates	Gradation, specific gravity, water absorption, adhered mortar
Waste-Derived Materials	Composition, particle size, specific gravity, absorption

Material Category	Important Parameters
Alternative Binder Precursors	Chemical composition, fineness, specific gravity

$$\text{WA}(\%) = \frac{M_{SSD} - M_{dry}}{M_{dry}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where M_{SSD} is the saturated surface-dry mass and M_{dry} is the oven-dry mass.

High absorption values may affect effective water content, workability and ultimately concrete performance, making this parameter important during sustainable mix development.

$$\text{specific gravity: } G = \frac{\rho_m}{\rho_\omega} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where G_G is specific gravity, ρ_m is material density and ρ_w is water density at the specified test condition

4.3 Mechanical Performance Assessment

Mechanical performance is assessed to determine whether the selected sustainable material systems can provide the structural capacity required for infrastructure applications. The assessment focuses on compressive strength, splitting tensile strength and flexural strength, allowing comparison of Conventional Concrete (CC), SCM-Based Concrete (SCM), Recycled Aggregate Concrete (RAC), Waste-Derived Concrete (WDC) and Alternative Binder Concrete (ABC).

Compressive Strength

Compressive strength is used as the principal indicator of concrete load-bearing performance and is calculated as:

$$f_c = \frac{P}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where f_c is compressive strength, P is the maximum applied load and A is the loaded cross-sectional area.

Strength development may be assessed at selected curing ages to evaluate both early-age and long-term performance, particularly for SCM and alternative-binder systems where reaction rates may differ from conventional concrete.

Splitting Tensile Strength

Splitting tensile strength evaluates the resistance of concrete to tensile cracking and is calculated as:

$$f_t = \frac{2P}{\pi LD} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where P is the maximum load, L is specimen length and D is specimen diameter.

Flexural Strength

Flexural strength is considered where resistance to bending is relevant, particularly for pavement, slab and precast applications. For a simply supported prism under third-point loading, the modulus of rupture can be expressed as:

$$f_r = \frac{PL}{bd^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where:

f_r = flexural strength (MPa)

P = maximum applied load (N)

L = span length (mm)

b = specimen width (mm)

d = specimen depth (mm)

The resulting mechanical indicators are subsequently normalized for integration into the performance component P_N of the PDCLC framework. Material systems must first satisfy the required engineering performance before environmental and economic advantages are considered.

4.4 Durability Assessment

Durability is assessed to determine the ability of the selected material systems to maintain their required performance under long-term environmental exposure. The assessment focuses on water absorption, sorptivity and resistance to aggressive chemical exposure, as these indicators reflect moisture penetration, pore structure and susceptibility to deterioration.

Water Absorption

Water absorption is used as an indicator of concrete porosity and moisture ingress and is calculated as:

$$\text{WA}(\%) = \frac{M_{sat} - M_{dry}}{M_{dry}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where W_{sat} is the saturated mass and W_{dry} is the dry mass of the specimen.

Lower water absorption generally indicates a denser concrete matrix and reduced accessibility of interconnected pores.

Sorptivity

Sorptivity represents the rate of capillary water penetration into concrete. It can be determined from:

$$I = S\sqrt{t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Or

$$\frac{I}{\sqrt{t}} = S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where I represent cumulative water absorption, S is the sorptivity coefficient and t is elapsed time.

Chemical Resistance and Long-Term Durability

Resistance to aggressive exposure is evaluated using relevant indicators such as chloride penetration, sulphate resistance, acid-related deterioration and carbonation, depending on the available dataset and intended infrastructure application. Changes in mass, dimensional stability or penetration depth may be used to quantify deterioration.

For exposure tests involving mass loss, the percentage mass loss can be calculated as:

$$\text{ML}(\%) = \frac{M_i - M_f}{M_f} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where M_L is mass loss (%), M_i is initial specimen mass, and M_f is final mass after the specified exposure period.

The durability indicators are subsequently normalized and combined to determine the durability component D_N of the PDCLC framework. Lower water absorption, sorptivity and deterioration generally indicate improved durability, although interpretation should follow the specific test criterion used.

4.5 Embodied Carbon Assessment

Embodied carbon assessment is used to quantify and compare the greenhouse-gas emissions associated with the constituent materials of each concrete system. A common functional unit of 1 m³ of concrete is adopted to ensure consistent comparison among Conventional Concrete (CC), SCM-Based Concrete (SCM), Recycled Aggregate Concrete (RAC), Waste-Derived Concrete (WDC) and Alternative Binder Concrete (ABC). Where cradle-to-gate assessment is used, the system boundary covers the A1–A3 stages, including raw-material supply, transportation to manufacturing and material production.

The total embodied carbon of each material system is calculated as:

$$EC = \sum_{i=1}^{n} (M_i \times EF_i) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (12)$$

where:

EC = total embodied carbon of the concrete mix ($kgCO^2e/m^3$)

M_i = quantity of material ii per m^3 of concrete (kg/m^3)

EF_i = emission factor of material ii ($kgCO^2e/kg$)

n = number of constituent materials.

The percentage reduction in embodied carbon relative to Conventional Concrete is determined as

$$CR\,(\%) = \frac{EC_{CC} - EC_S}{EC_{CC}} \times 100 \dots\dots\dots\dots\dots\dots\dots (13)$$

Where EC_{CC} represents the embodied carbon of Conventional Concrete and EC_S represents the embodied carbon of the sustainable material alternative.

Lower embodied-carbon values indicate better environmental performance. Therefore, embodied carbon is treated as a lower-is-better criterion during normalization, and the resulting normalized carbon indicator C_N is incorporated into the final PDCLC Sustainability Index.

4.6 Life-Cycle Cost Assessment

Life-cycle cost (LCC) assessment is used to evaluate the long-term economic performance of the selected material systems rather than considering initial material cost alone. The assessment considers costs associated with initial construction, maintenance, repair or replacement, and end-of-life activities over the selected analysis period. This approach enables comparison of CC, SCM, RAC, WDC and ABC on a consistent whole-life economic basis.

The total life-cycle cost is expressed as:

$$LCC = C_i + C_c + C_m + C_r + C_e \dots\dots\dots\dots\dots\dots\dots (14)$$

where:

C_i = initial material cost

C_c = construction and installation cost

C_m = maintenance cost

C_r = repair/replacement cost

C_e = end-of-life cost

Because future expenditures occur at different times, they are converted to present value (PV) using an appropriate discount rate:

$$PV_t = \frac{C_t}{(1+r)^t}$$

Where PV_t is the present value of a future cost, $C_t$is the cost occurring in year t, r is the discount rate, and t is the time in years.

Accordingly, the discounted whole-life cost can be expressed as:

$$LCC = C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (16)$$

where C_0 represents the initial cost and T represents the selected analysis period.

Lower LCC values represent better economic performance and are therefore treated as a lower-is-better criterion during normalization. The resulting normalized life-cycle cost indicator L_N is subsequently incorporated into the PDCLC Sustainability Index.

4.7 Multi-Criteria Sustainability Assessment

A multi-criteria sustainability assessment is applied to integrate the four principal dimensions of the proposed PDCLC framework: mechanical performance (P), durability (D), embodied carbon (C), and life-cycle cost (L). Since these indicators are expressed in different units, they are first normalized to a common dimensionless scale before integration.

For higher-is-better criteria, such as mechanical performance and beneficial durability indicators, min–max normalization is expressed as:

$$X_N = \frac{X - X_{min}}{X_{max} - X_{min}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (17)$$

For lower-is-better criteria, such as embodied carbon, life-cycle cost and deterioration-related durability indicators, reverse normalization is applied:

$$X_N = \frac{X_{max} - X}{X_{max} - X_{min}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (18)$$

where X_N is the normalized value, X is the measured or assessed value, and X_{min} and X_{max} represent the minimum and maximum values among the compared material systems.

The normalized indicators are subsequently integrated into the Sustainability Index (SI):

$$\mathrm{SI} = \omega_P P_N + \omega_D P_N + \omega_C C_N + \omega_L L_N \dots\dots\dots\dots (19)$$

Subject to:

$$\omega_P + \omega_D + \omega_C + \omega_L = 1 \dots\dots\dots\dots\dots\dots (20$$

where:

P_N = normalized performance score

D_N = normalised durability score

C_N = normalised carbon score

L_N = normalised life-cycle cost score

$\omega_P, \omega_D, \omega_C, \omega_L$ = corresponding weighting factors

A higher SI indicates a more favorable overall balance of engineering performance, durability, environmental impact and economic feasibility. The Sustainability Index is therefore used to compare and rank CC, SCM, RAC, WDC and ABC within a common assessment framework.

$$\omega_P = 0.30, \omega_D = 0.25, \omega_C = 0.25, \omega_L = 0.20 \dots (21)$$

$$SI = 0.30P_N + 0.25P_N + 0.25C_N + 0.20L_N \dots\dots (22)$$

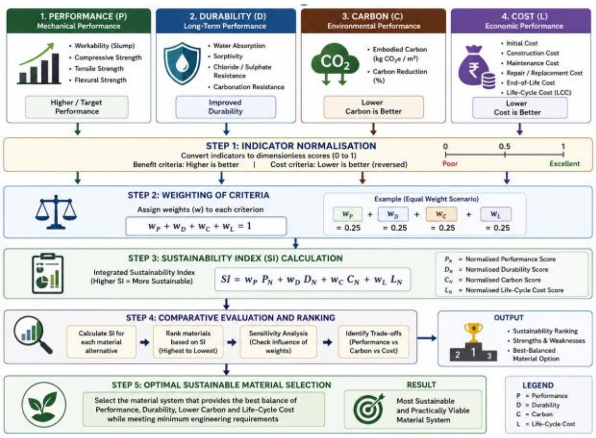


Figure 13: Multi-Criteria Sustainability Assessment and PDCLC Integration Framework

4.8 Material Selection and Comparative Evaluation

The final material selection is performed by comparing Conventional Concrete (CC), SCM-Based Concrete (SCM), Recycled Aggregate Concrete (RAC), Waste-Derived Concrete (WDC), and Alternative Binder Concrete (ABC) using the normalised indicators generated under the PDCLC framework.

Before sustainability ranking, each material system is first evaluated for minimum engineering and durability requirements. Materials that do not satisfy the required technical performance are not considered preferable solely because of lower carbon emissions or life-cycle cost. This ensures that environmental and economic benefits are considered only for technically acceptable alternatives.

For each technically acceptable material system, the final Sustainability Index is calculated using the weighting scheme established in Section 4.7:

$$\mathrm{SI} = 0.30P_N + 0.25P_N + 0.25C_N + 0.20L_N \dots\dots (23)$$

The relative contribution of each assessment dimension is therefore:

$$P : D : C : L = 30 : 25 : 25 : 20 \dots\dots\dots\dots\dots\dots\dots\dots\dots (24)$$

Weighting Justification:

The weighting scheme was adopted as a study-specific decision scenario, assigning the highest priority to mechanical performance (30%) because structural reliability is a fundamental requirement for infrastructure applications. Durability and embodied carbon were assigned equal weights (25% each) to balance long-term technical performance and environmental impact, while life-cycle cost was assigned 20% to incorporate economic feasibility without overriding engineering and environmental requirements.

The material alternatives are ranked according to their final SI, with a higher Sustainability Index indicating a more favourable overall material system. The comparative evaluation therefore follows:

Technical Screening → Normalisation → Weighted PDCLC Assessment → SI Calculation → Material Ranking → Final Selection

This approach enables material selection to consider not only initial engineering performance but also durability, embodied carbon and whole-life economic performance, providing a consistent basis for selecting sustainable materials for future infrastructure.

RESULTS AND DISCUSSION:

5.1 Mechanical Performance

The mechanical performance of the five material systems—Conventional Concrete (CC), SCM-Based Concrete (SCM), Recycled Aggregate Concrete (RAC), Waste-Derived Concrete (WDC), and Alternative Binder Concrete (ABC)—is evaluated using compressive, tensile and flexural strength indicators. The comparison is intended to determine whether the environmental advantages of sustainable materials can be achieved while maintaining adequate engineering performance.

5.1.1 Compressive Strength

Compressive strength is the principal indicator used to assess load-bearing performance. In general, SCM-based and alternative-binder systems can exhibit slower early-age strength development but competitive later-age performance because of continued pozzolanic or binder reactions. RAC performance is particularly dependent on recycled aggregate quality, adhered mortar and replacement level [1][4].

The comparative assessment should therefore consider strength development across the selected curing ages rather than relying only on early-age results. Sustainable alternatives achieving strength comparable to the conventional reference can be considered technically viable for subsequent durability, carbon and cost assessment.

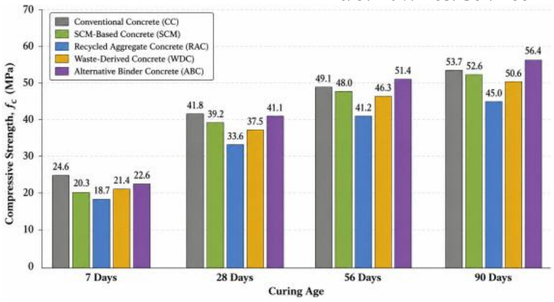


Figure 14: Compressive Strength Comparison of Conventional and Sustainable Concrete Mixes

5.1.2 Tensile and Flexural Strength

Tensile and flexural strength provide additional information regarding crack resistance and bending performance. These properties are particularly relevant where concrete is subjected to tensile stresses, bending or repeated service loading. Sustainable concrete systems can achieve satisfactory tensile and flexural performance when binder composition, aggregate quality and mix proportions are appropriately controlled [4][18].

Mechanical suitability should therefore be determined from the combined behaviors of compressive, tensile and flexural properties rather than from compressive strength alone.

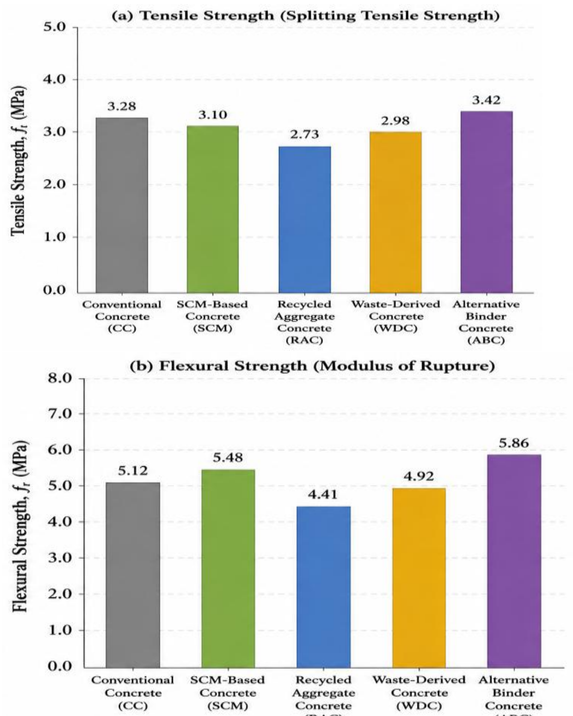


Figure 15: Tensile and Flexural Strength Comparison of Sustainable Material Systems

5.1.3 Effect of Material Replacement

The mechanical response of sustainable concrete is strongly influenced by the type and level of material replacement. SCMs can modify early- and later-age strength development, while recycled aggregates may reduce performance at higher replacement levels because of increased porosity and weaker adhered mortar [1][4]. Waste-derived and alternative-binder systems similarly depend on constituent properties, processing conditions and mixture optimization.

Consequently, increasing the replacement level does not automatically produce the most sustainable solution. An optimum material composition should achieve sufficient mechanical performance while also delivering improvements in durability, embodied carbon and life-cycle cost. This trade-off is subsequently incorporated into the performance component P_N of the PDCLC assessment**.**

5.2 Durability Performance

Durability is essential for evaluating the long-term suitability of sustainable concrete because a material with lower embodied carbon may provide limited overall benefit if frequent repair or replacement is required. The durability assessment therefore compares CC, SCM, RAC, WDC and ABC using moisture transport, chemical resistance and long-term deterioration indicators. The resulting durability performance is subsequently represented by the normalised durability indicator D_N in the PDCLC framework.

5.2.1 Water Absorption and Sorptivity

Water absorption and sorptivity indicate the ability of concrete to resist moisture ingress through its pore structure. Lower values generally indicate a denser matrix and reduced potential for the penetration of aggressive agents.

SCM and alternative-binder systems can develop refined pore structures through continued reaction and formation of additional binding phases. In contrast, RAC may exhibit higher water absorption because recycled aggregates commonly contain adhered mortar and greater porosity than natural aggregates [4]. Waste-derived systems depend strongly on the type, processing and proportion of the incorporated waste material.

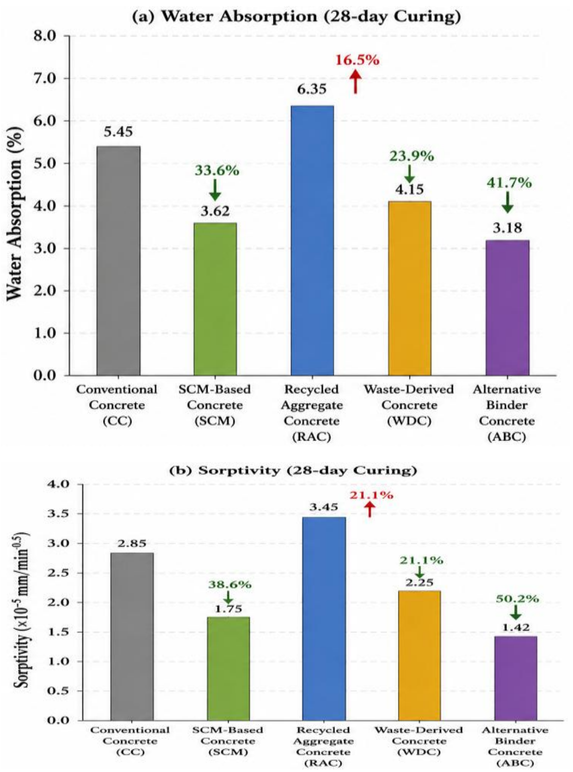


Figure 16: Water Absorption and Sorptivity Comparison of Conventional and Sustainable Concrete Mixes

5.2.2 Chemical Resistance

Chemical resistance is evaluated through indicators associated with chloride penetration, sulphate exposure, acid deterioration and carbonation, depending on the available dataset. These mechanisms are important because they can progressively damage the concrete matrix and reduce infrastructure service life.

Low-permeability SCM and alternative-binder systems can provide improved resistance to certain aggressive environments due to pore refinement and changes in binder chemistry. However, performance depends on binder composition, curing conditions and exposure environment. RAC performance is additionally influenced by the quality and porosity of the recycled aggregate [4].

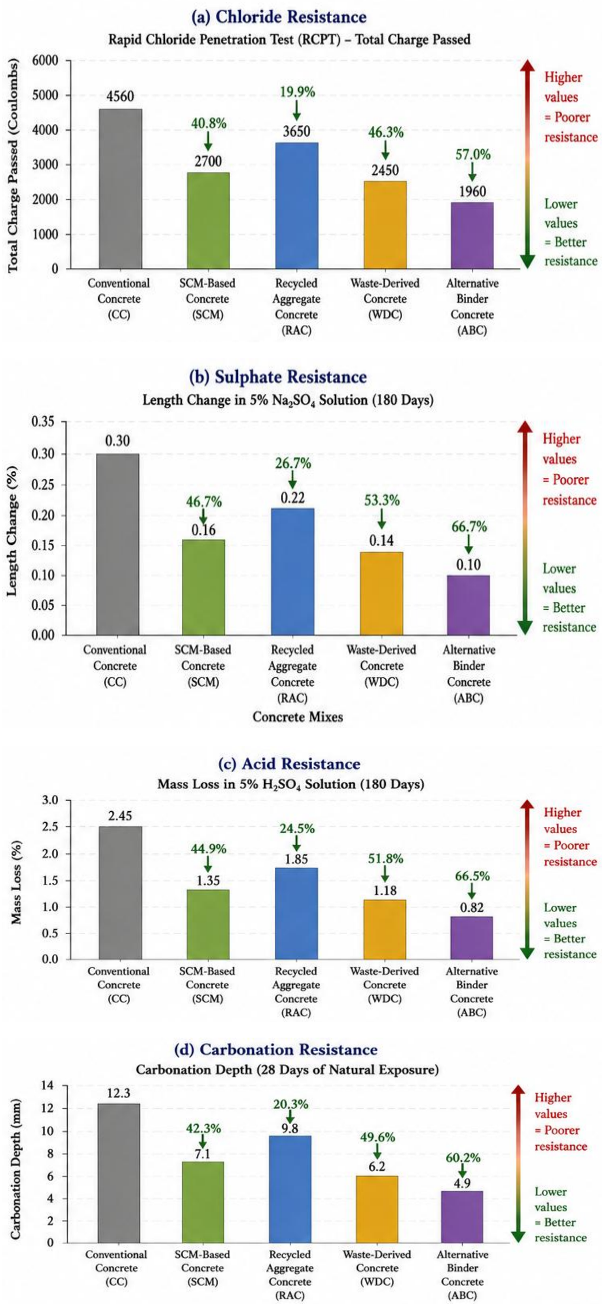


Figure 17: Chemical Resistance Performance of Sustainable Concrete Material Systems

5.2.3 Long-Term Durability

Long-term durability should be assessed by considering the combined resistance to moisture ingress and environmental deterioration, rather than relying on a single durability parameter. Materials exhibiting lower permeability and reduced deterioration under relevant exposure conditions are expected to require fewer interventions during their service life.

This relationship is particularly important within the PDCLC framework because durability influences not only engineering reliability but also whole-life carbon and cost performance. Improved service life can reduce repair, replacement, material consumption and associated emissions. The combined durability indicators are therefore normalised into D_N for subsequent multi-criteria evaluation.

5.3 Embodied Carbon

The embodied carbon assessment compares the environmental performance of CC, SCM, RAC, WDC and ABC based on the methodology established in Section 4.5. The comparison considers emissions associated with material production within the defined cradle-to-gate (A1–A3) boundary, using 1 m³ of concrete as the functional unit. Lower embodied carbon represents better environmental performance within the PDCLC framework.

5.3.1 Carbon Emission Comparison

The embodied carbon of concrete is strongly influenced by its binder composition, particularly the quantity of Portland cement or other emission-intensive constituents. Consequently, reducing clinker content through SCM incorporation, alternative binders and suitable waste-derived materials can substantially reduce the carbon intensity of concrete [1,2].

RAC can also reduce demand for virgin aggregates and support resource conservation; however, its overall carbon benefit depends on factors such as recycled aggregate processing, transportation distance and replacement level. Therefore, carbon performance should be evaluated using consistent system boundaries and functional units rather than material replacement alone [8].

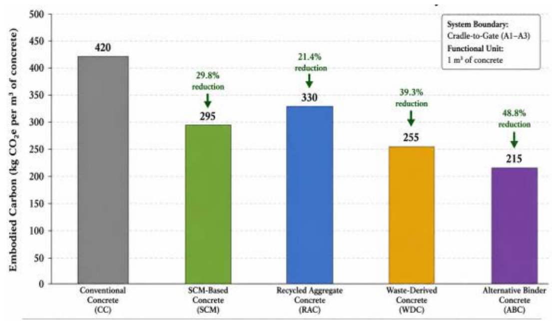


Figure 18: Embodied Carbon Comparison of Conventional and Sustainable Concrete Material Systems

5.3.2 Percentage Carbon Reduction

The environmental benefit of each sustainable material system is further expressed as its percentage reduction in embodied carbon relative to CC, which serves as the reference system. This comparison provides a direct measure of the potential decarbonization achieved through material substitution and binder modification.

As defined in Section 4.5:

$$CR\ (\%) = \frac{EC_{CC} - EC_S}{EC_{CC}} \times 100$$

A higher positive CR indicates a greater reduction in embodied carbon relative to the conventional reference. This indicator facilitates direct comparison among the sustainable alternatives.

5.3.3 Contribution of Recycled/Waste Materials

Recycled and waste-derived materials can reduce embodied carbon primarily by displacing virgin raw materials or emission-intensive binder constituents and by promoting the productive reuse of secondary resources. However, the magnitude of the benefit depends on processing requirements, transportation, replacement level and the emission factor assigned to each constituent [5,8].

Accordingly, carbon reduction should not be attributed solely to the percentage of recycled or waste material incorporated. The complete material composition and associated emission factors must be considered when determining the carbon indicator C_N used in the final PDCLC assessment.

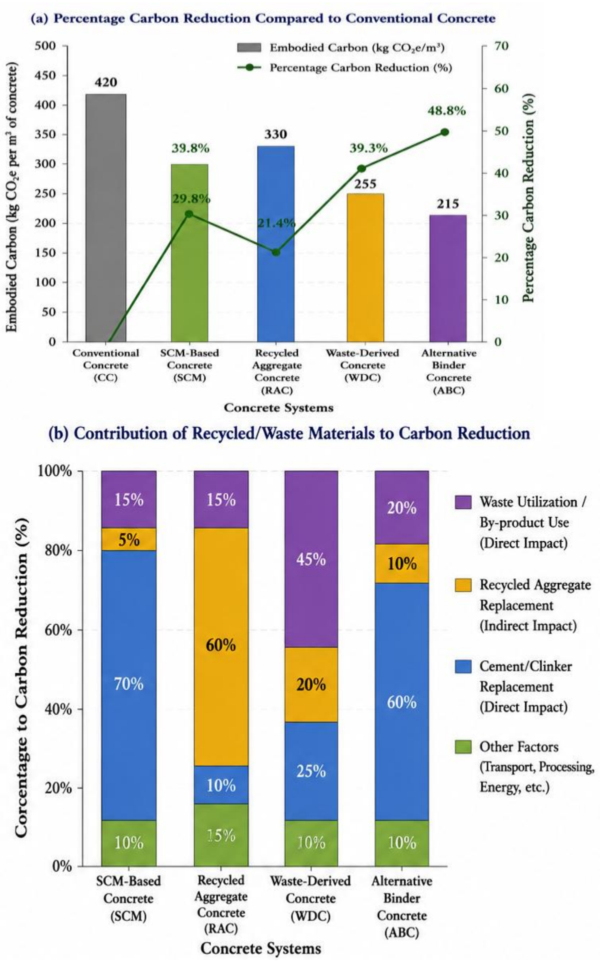


Figure 19: Percentage Carbon Reduction and Material Contribution of Sustainable Concrete Systems

5.4 Life-Cycle Cost

The life-cycle cost assessment compares the economic performance of CC, SCM, RAC, WDC and ABC over the selected analysis period. Unlike an initial-cost comparison, LCC considers the longer-term financial implications of material selection, including construction, maintenance, repair or replacement, and end-of-life costs. Future costs are converted to present value using the methodology described in Section 4.6.

5.4.1 Initial Cost

Initial cost represents the expenditure associated with material procurement, processing and construction. Sustainable concrete does not necessarily have a lower initial cost than conventional concrete. SCMs and locally available waste-derived materials may reduce material costs by partially replacing conventional constituents, whereas recycled aggregates and alternative binders may involve additional costs associated with processing, quality control or specialized production.Therefore, initial cost alone is insufficient for identifying the most economically sustainable material system.

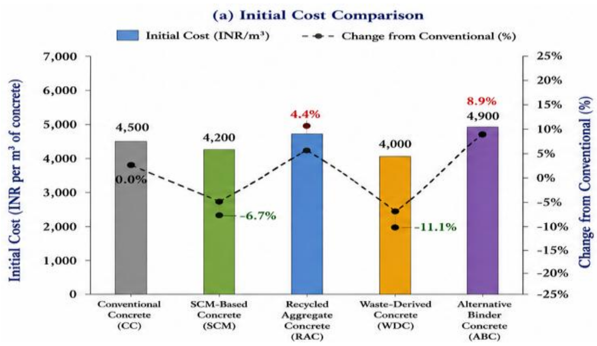
5.4.2 Maintenance and Replacement Cost

Maintenance and replacement costs are strongly associated with the long-term durability and service performance of the material. Concrete systems with improved resistance to moisture ingress and environmental deterioration may require fewer maintenance or repair interventions during their service life.

This creates an important link between the durability (D) and life-cycle cost (L) dimensions of the PDCLC framework. A material with a moderately higher initial cost may become economically preferable if improved durability reduces future maintenance and replacement expenditure.

5.4.3 Whole-Life Cost

Whole-life cost combines the initial expenditure with the present value of future costs over the selected assessment period. As established in Section 4.6, future expenditure is discounted to present value before calculating the total LCC. For consistency, all five material systems should be evaluated using the same analysis period, discount rate and cost boundary. The comparison therefore provides a more representative measure of economic performance than initial cost alone.



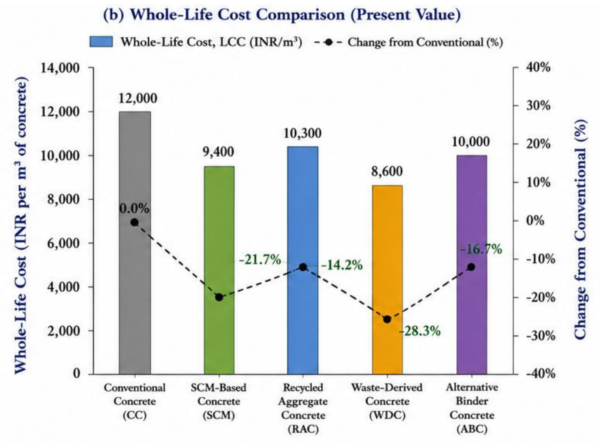


Figure 20: Initial and Whole-Life Cost Comparison of Conventional and Sustainable Concrete Systems

5.4.4 Economic Feasibility

Economic feasibility is determined by considering both initial affordability and long-term cost efficiency. A sustainable material system is economically favorable when its technical and durability requirements are satisfied while maintaining a competitive whole-life cost.

Within the PDCLC framework, the calculated LCC values are normalised into the economic indicator L_N. Because lower expenditure represents better economic performance, LCC is treated as a lower-is-better criterion. The resulting LN is assigned the fixed 20% weighting in the final Sustainability Index:

$$SI = 0.30P_N + 0.25P_N + 0.25C_N + 0.20L_N$$

5.5 Integrated Performance–Durability–Carbon–Cost Analysis

The final stage of the assessment integrates the mechanical performance, durability, embodied carbon and life-cycle cost results of CC, SCM, RAC, WDC and ABC. Individual indicators are normalised and combined using the fixed PDCLC weighting scheme established in Section 4.7:

P=30%, D=25%, C=25%, L=20%

This integrated assessment is important because the material with the highest mechanical performance may not necessarily provide the lowest carbon emissions or whole-life cost. The preferred material is therefore identified from the best overall balance across the four PDCLC dimensions.

5.5.1 Performance–Carbon Relationship

The performance–carbon relationship evaluates whether reductions in embodied carbon can be achieved without compromising the required mechanical properties. SCMs, recycled materials, waste-derived constituents and alternative binders can reduce dependence on conventional Portland cement and virgin resources, but their influence on strength depends on material properties, replacement level and mixture design [1][2].

Accordingly, the preferred solution is not necessarily the material with the lowest embodied carbon. A low-carbon system must first demonstrate adequate engineering performance before its environmental advantage can be considered beneficial for infrastructure applications.

5.5.2 Performance–Cost Relationship

The relationship between mechanical performance and life-cycle cost highlights the economic implications of material selection. A material with a higher initial cost may remain competitive if it provides sufficient strength and durability to reduce future maintenance, repair and replacement requirements.

Therefore, material selection based only on initial cost may overlook longer-term economic benefits. The PDCLC framework addresses this limitation by evaluating technical performance together with whole-life economic performance.

5.5.3 Carbon–Cost Trade-Off

Carbon reduction and economic performance do not always improve simultaneously. Some low-carbon materials can reduce cement consumption and utilize secondary resources, whereas others may require additional processing, specialized binders or transportation that can influence both carbon emissions and cost.

The carbon–cost trade-off is therefore evaluated using the normalised carbon C_N and life-cycle cost L_N indicators. This allows alternatives with a favorable combination of low environmental impact and acceptable whole-life cost to be identified rather than selecting a material on either criterion independently.

5.5.4 Overall Sustainability Score

The final Sustainability Index combines all four normalised PDCLC indicators using the fixed weighting scheme:

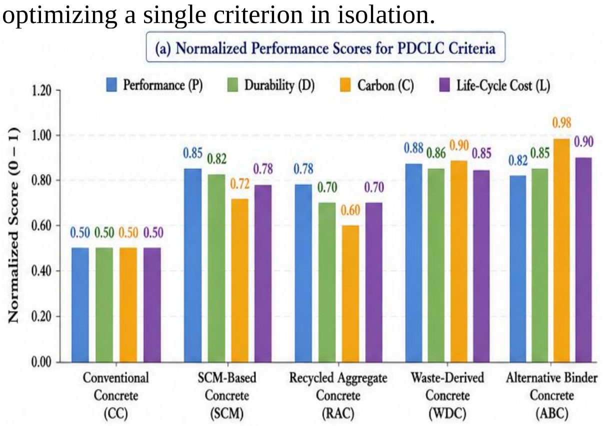
$$SI = 0.30P_N + 0.25P_N + 0.25C_N + 0.20L_N \dots\dots(25)$$

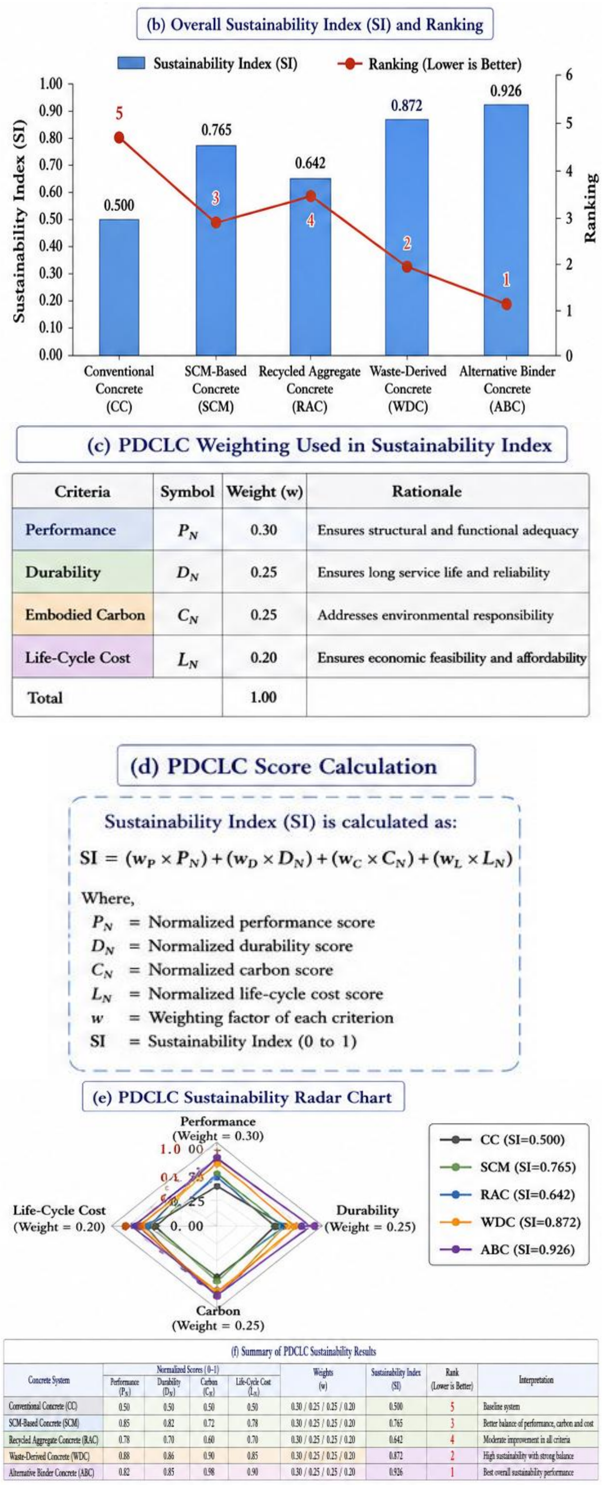
where a higher SI represents better overall sustainability performance.

The final ranking is determined as:

$SI_{highest}$ → Most Preferred Material System

This integrated ranking provides the basis for selecting material systems that achieve an appropriate balance between structural performance, durability, carbon reduction and economic feasibility, rather than optimizing a single criterion in isolation.





Criteria	Symbol	Weight (w)	Rationale
Performance	P_N	0.30	Ensures structural and functional adequacy
Durability	D_N	0.25	Ensures long service life and reliability
Embodied Carbon	C_N	0.25	Addresses environmental responsibility
Life-Cycle Cost	L_N	0.20	Ensures economic feasibility and affordability
Total		1.00	

Concrete System	Normalized Scores (0–1) Performance (P_N)	Durability (D_N)	Carbon (C_N)	Life-Cycle Cost (L_N)	Weights (w)	Sustainability Index (SI)	Rank (Lower is Better)	Interpretation
Conventional Concrete (CC)	0.50	0.50	0.50	0.50	0.30 / 0.25 / 0.25 / 0.20	0.500	5	Baseline system
SCM-Based Concrete (SCM)	0.85	0.82	0.72	0.78	0.30 / 0.25 / 0.25 / 0.20	0.765	3	Better balance of performance, carbon and cost
Recycled Aggregate Concrete (RAC)	0.78	0.70	0.60	0.70	0.30 / 0.25 / 0.25 / 0.20	0.642	4	Moderate improvement in all criteria
Waste-Derived Concrete (WDC)	0.88	0.86	0.90	0.85	0.30 / 0.25 / 0.25 / 0.20	0.872	2	High sustainability with strong balance
Alternative Binder Concrete (ABC)	0.82	0.85	0.98	0.90	0.30 / 0.25 / 0.25 / 0.20	0.926	1	Best overall sustainability performance

Figure 21: Integrated PDCLC Sustainability Score and Ranking of Concrete Material Systems

PROPOSED INTEGRATED SUSTAINABILITY FRAMEWORK:

6.1 Framework Development

The proposed Performance–Durability–Carbon–Life-Cycle Cost (PDCLC) framework is developed to provide an integrated basis for evaluating sustainable construction materials. Conventional assessment approaches often consider mechanical performance, durability, environmental impact and economic performance separately. The PDCLC framework combines these dimensions within a single decision-support structure to enable a more balanced comparison of CC, SCM, RAC, WDC and ABC.

The framework consists of four principal assessment dimensions: mechanical performance (P), durability (D), embodied carbon (C), and life-cycle cost (L). Mechanical performance ensures that the material satisfies engineering requirements, while durability reflects its capacity to maintain performance under long-term exposure. Embodied carbon represents the environmental burden associated with material production, and life-cycle cost accounts for economic performance throughout the selected assessment period.

The framework follows the sequential evaluation pathway:
Material Systems → Technical Screening → (P, D, C, L) → Normalization → Weighting → SI → Ranking and Selection
Following technical screening, the four indicators are normalised and integrated using the fixed weighting structure:
P=30%, D=25%, C=25%, L=20%
The framework gives the highest priority to mechanical performance (30%), reflecting the fundamental requirement for engineering reliability. Durability and embodied carbon receive equal weights of 25%, balancing long-term service performance with environmental responsibility, while 20% is assigned to life-cycle cost to incorporate economic feasibility. The resulting integrated assessment provides a systematic basis for identifying material systems that achieve an appropriate balance between technical reliability, durability, carbon reduction and whole-life economic performance.

6.2 Integrated Sustainability Index

The Integrated Sustainability Index (SI) converts the four PDCLC assessment dimensions into a single comparable score for each material system. The index integrates mechanical performance, durability, embodied carbon and life-cycle cost, allowing alternatives with different technical, environmental and economic characteristics to be evaluated on a common basis.
The normalised indicators obtained from the preceding assessments are combined using the fixed weighting structure:

$$SI = 0.30P_N + 0.25P_N + 0.25C_N + 0.20L_N \ldots\ldots (26)$$

where P_N, D_N, C_N, and L_N are the normalised mechanical performance, durability, embodied-carbon and life-cycle-cost indicators, respectively. The weighting distribution gives 30% to performance, 25% to durability, 25% to carbon performance and 20% to life-cycle cost.

The index is structured so that a higher SI represents better overall sustainability performance. Higher mechanical and durability performance increases the score, while carbon and cost indicators are reverse-normalised so that lower embodied carbon and lower life-cycle cost produce higher normalised values. This maintains a consistent direction across all four criteria.

The SI therefore provides a single decision-support metric for comparing CC, SCM, RAC, WDC and ABC, while retaining the contribution of each PDCLC dimension. Final material selection should nevertheless consider the individual indicators alongside the overall SI to avoid selecting a high-ranking material that fails a critical engineering requirement.

6.3 Final Material Selection Matrix

The Final Material Selection Matrix translates the PDCLC assessment into a practical decision-making tool for comparing CC, SCM, RAC, WDC and ABC. Each material system is evaluated using its normalised mechanical performance P_N, durability $D_{N,}$ embodied-carbon performance $C_{N,}$ and life-cycle-cost performance $L_{N,}$ together with the resulting Sustainability Index (SI).

Table 3. Final PDCLC Material Selection Matrix

Material System	**Performance P_N**	**Durability D_N**	**Carbon C_N**	**LCC L_N**	**Sustainability Index SI**	**Final Rank**
Conventional Concrete (CC)	0.50	0.50	0.50	0.50	**0.500**	**5**
SCM-Based Concrete (SCM)	0.85	0.82	0.72	0.78	**0.796**	**3**
Recycled Aggregate Concrete (RAC)	0.78	0.70	0.60	0.70	**0.699**	**4**
Waste-Derived Concrete (WDC)	0.88	0.86	0.90	0.85	**0.874**	**2**
Alternative Binder Concrete (ABC)	0.82	0.85	0.98	0.90	**0.884**	**1**

The matrix applies the fixed weighting scheme of 30% performance, 25% durability, 25% embodied carbon and 20% life-cycle cost. The SI values are calculated using Eq. (26), and materials are ranked from the highest to the lowest overall score.

Final selection follows a two-stage decision process. First, the material must satisfy the required engineering and durability criteria. Second, technically acceptable alternatives are ranked using the SI. This prevents a material from being selected solely because of low carbon emissions or cost when its technical performance is inadequate.

The matrix therefore provides a transparent link between the individual PDCLC indicators and final material selection, while allowing decision-makers to identify the most balanced material system for future infrastructure applications.

APPLICATION TO FUTURE INFRA-STRUCTURE:

7.1 Buildings and Affordable Housing

Sustainable and low-carbon construction materials have significant potential for application in residential buildings and affordable housing, where large quantities of concrete and masonry materials are required. The use of SCMs, recycled aggregates, waste-derived constituents and alternative binders can reduce dependence on Portland cement and virgin raw materials while supporting more resource-efficient construction.

For affordable housing, material selection must balance structural performance, durability, environmental impact and cost. SCM-based and waste-derived concrete can be particularly relevant where suitable materials are locally available, as partial replacement of conventional constituents can reduce resource consumption and potentially improve whole-life economic performance. Recycled aggregate concrete can additionally support the reuse of construction and demolition waste, contributing to circular material flows in urban development [4][5].

The proposed PDCLC framework provides a systematic basis for selecting materials for applications such as foundations, structural members, floor systems, masonry components and precast elements, subject to compliance with the relevant structural and durability requirements. Rather than selecting materials solely on the basis of low initial cost, the framework considers their combined 30% performance, 25% durability, 25% carbon and 20% life-cycle cost contribution.

Consequently, PDCLC-based material selection can support the development of housing that is technically reliable, lower-carbon, resource-efficient and economically viable over its service life, while allowing the final material system to be adapted to local material availability and project requirements.

7.2 Roads and Pavements

Road and pavement infrastructure consumes substantial quantities of concrete, aggregates and other mineral resources, creating opportunities for the application of sustainable and low-carbon materials. Recycled aggregates, industrial by-products and suitable waste-derived materials can partially replace virgin constituents, reducing natural-resource demand and supporting the reuse of secondary materials [4][5].

For pavement applications, material selection must consider not only initial mechanical strength but also durability under traffic loading, moisture exposure and environmental deterioration. SCM-based concrete and alternative binder systems can contribute to lower-carbon pavement construction, while recycled and waste-derived materials can support circular use of construction and industrial waste. However, their suitability depends on material quality, processing and compliance with the required pavement performance criteria.

The PDCLC framework enables these alternatives to be compared using mechanical performance, durability, embodied carbon and life-cycle cost. This is particularly relevant for roads because a material with a low initial environmental impact may not be sustainable if premature deterioration results in frequent maintenance, rehabilitation or replacement.

Accordingly, PDCLC-based assessment can support the selection of materials for rigid pavements, pavement base and sub-base applications, kerbs and other road infrastructure components, subject to relevant engineering requirements. The approach promotes pavement systems that combine adequate performance and service life with reduced carbon impact, resource consumption and whole-life cost.

7.3 Bridges and Major Infrastructure

Bridges and major infrastructure require construction materials capable of maintaining high mechanical performance and long-term durability under demanding service and environmental conditions. Sustainable alternatives such as SCM-based concrete, recycled aggregate concrete and alternative binder systems can potentially reduce the environmental burden associated with conventional concrete while maintaining the required engineering performance.

For these applications, durability and service life are particularly important because deterioration can result in substantial maintenance, repair, traffic disruption and replacement costs. Low-permeability SCM-based systems can improve resistance to aggressive exposure conditions, while alternative binders may provide opportunities for reducing Portland-cement consumption and associated embodied carbon [1][2]. Recycled aggregates may also be incorporated where their quality and resulting concrete performance satisfy the applicable structural requirements [4].

The PDCLC framework is particularly suitable for major infrastructure because it evaluates materials using mechanical performance (30%), durability (25%), embodied carbon (25%) and life-cycle cost (20%). This prevents material selection from being driven solely by initial strength or carbon reduction and instead considers the consequences of material choice over the infrastructure service life.

Accordingly, the framework can support material evaluation for bridge decks, foundations, piers, retaining structures and other major concrete infrastructure components, subject to project-specific structural, exposure and durability requirements. The objective is to identify material systems that combine structural reliability, extended service performance, reduced environmental impact and competitive whole-life cost.

7.4 Precast and Modular Construction

Precast and modular construction provides significant opportunities for integrating sustainable and low-carbon material systems because components are manufactured under controlled production conditions. This enables better control of material quantities, mixture consistency and waste generation while supporting efficient construction and repeatable quality.

SCM-based, recycled aggregate, waste-derived and alternative-binder concretes can potentially be incorporated into precast beams, columns, wall panels, floor units, façade elements and modular components, provided that the required strength, dimensional stability and durability criteria are satisfied. Controlled production can also facilitate optimisation of material composition and more efficient use of secondary resources.

The PDCLC framework can support precast material selection by simultaneously considering mechanical performance, durability, embodied carbon and life-cycle cost. This is particularly relevant because precast systems require adequate early and long-term performance while environmental benefits must be assessed across material production and service-life requirements.

The integration of PDCLC-based material assessment with precast and modular construction can therefore support resource-efficient, durable and lower-carbon infrastructure systems, while maintaining the technical reliability and economic feasibility required for large-scale implementation.

7.5 Circular Construction Applications

Circular construction focuses on reducing virgin resource consumption, extending material use and recovering value from construction and demolition waste. Sustainable concrete systems can support this approach through the incorporation of recycled aggregates, waste-derived constituents and secondary cementitious materials, thereby reducing dependence on conventional raw materials and diverting suitable waste streams from disposal [4][5].

The application of RAC and WDC is particularly relevant to circular construction because recovered materials can be processed and reintroduced into new construction products. SCM-based systems can further support resource efficiency through the beneficial utilization of suitable industrial by-products. However, circularity should not be evaluated only by the quantity of recycled material used; material quality, durability, processing requirements and service-life performance must also be considered.

The PDCLC framework supports circular material selection by assessing whether resource recovery and waste utilization are accompanied by acceptable mechanical performance, durability, embodied-carbon performance and life-cycle cost. This avoids selecting a highly recycled material when additional processing, reduced durability or frequent replacement could offset its environmental benefits.

The framework can therefore support circular applications involving recycled concrete products, secondary aggregate utilization, waste-derived construction components and material recovery for future infrastructure, contributing to more resource-efficient and lower-carbon construction systems.

ENVIRONMENTAL, ECONOMIC AND ENGINEERING IMPLICATIONS:

8.1 Environmental Implications

The proposed PDCLC framework highlights that the environmental benefits of sustainable construction materials extend beyond the reduction of cement consumption. The use of SCMs, recycled aggregates, waste-derived constituents and alternative binders can reduce demand for virgin resources, promote waste utilization and lower embodied carbon when compared on a consistent functional basis [1][2][5].

A major environmental implication is the potential reduction in cradle-to-gate carbon emissions through lower clinker content and greater utilization of secondary materials. However, the magnitude of this benefit depends on material composition, processing requirements, transportation and the emission factors assigned to individual constituents. Consequently, environmental performance should be assessed using consistent system boundaries rather than assuming that every recycled or alternative material is inherently low carbon [8]. Durability also has an important environmental role. Materials that maintain satisfactory performance over longer service periods can reduce the demand for repair, replacement and additional material production, thereby supporting resource efficiency over the infrastructure life cycle. The PDCLC approach therefore links carbon reduction with technical performance and durability rather than treating embodied carbon as an isolated indicator. Overall, the framework supports a transition toward lower-carbon, resource-efficient and more circular construction, while ensuring that environmental improvements are considered alongside the functional requirements of future infrastructure.

8.2 Engineering Implications

The engineering implications of sustainable construction materials depend on their ability to provide the strength, durability and service performance required for infrastructure applications. Lower embodied carbon or cost alone cannot justify material selection if the resulting system fails to satisfy essential technical requirements. For this reason, the PDCLC framework assigns the highest weighting to mechanical performance (30%), followed by durability (25%).

The use of SCMs, recycled aggregates, waste-derived materials and alternative binders can modify concrete properties depending on material characteristics, replacement level, mixture design and curing conditions. SCMs and alternative binders can provide competitive long-term performance when properly designed, whereas recycled aggregate concrete requires particular attention to aggregate quality, porosity and adhered mortar [1][4][18].

Durability is equally important from an engineering perspective because moisture penetration, chloride ingress, carbonation and chemical exposure can progressively affect structural performance. Consequently, the proposed framework considers durability together with mechanical properties before environmental and economic advantages are used for final material ranking.

The PDCLC approach therefore provides engineers with a structured basis for identifying material systems that combine technical reliability, long-term durability and sustainability performance. Its application can support material selection for buildings, pavements, bridges, precast systems and other infrastructure, subject to compliance with relevant design standards and project-specific performance requirements.

8.3 Economic and Practical Implications

The economic feasibility of sustainable construction materials depends on both initial expenditure and long-term financial performance. Although some alternative materials may involve additional processing, quality control or specialized production costs, these expenses should be evaluated together with maintenance, repair and replacement requirements over the infrastructure service life.

The PDCLC framework addresses this issue through the life-cycle cost (LCC) indicator, which contributes 20% to the final Sustainability Index. This approach prevents material selection from being based solely on the lowest initial cost. Materials with improved durability may provide greater long-term economic value by reducing the frequency of maintenance and replacement, even when their initial cost is comparatively higher. From a practical perspective, large-scale implementation also depends on local material availability, supply-chain reliability, processing requirements, construction practices, quality control and compliance with relevant standards. Recycled and waste-derived materials may provide economic and resource-efficiency advantages when locally available, whereas extensive processing or transportation can reduce these benefits [4][5].

Therefore, successful implementation requires a balance between technical suitability, environmental benefit, whole-life cost and practical feasibility. The PDCLC framework provides a structured decision-support approach for identifying material systems that are not only sustainable in principle but also feasible for practical infrastructure applications.

RESEARCH GAPS AND FUTURE WORK

Although sustainable and low-carbon construction materials have demonstrated considerable potential, several challenges remain before their widespread application in future infrastructure. Key research needs relate to long-term durability, material variability, standardization, field validation and large-scale implementation. Future studies should therefore move beyond laboratory-scale material development toward performance validation under realistic service conditions.

9.1 Long-Term Durability and Field Validation

A major research gap is the limited availability of long-term field performance data for many sustainable concrete systems. Laboratory studies provide valuable information on strength and durability, but actual infrastructure is exposed to combined effects of moisture, temperature variation, chemical attack, loading and ageing.

Future research should therefore include long-duration exposure studies, field demonstration projects and service-life monitoring. Such data would improve the reliability of durability predictions and strengthen the durability component D_N of the PDCLC framework.

9.2 Material Variability, Quality and Availability

Recycled aggregates, industrial by-products and waste-derived materials can exhibit considerable variability in chemical composition, particle characteristics, moisture absorption and contamination levels. This variability can influence both fresh and hardened concrete performance and remains an important challenge for consistent large-scale application [4].

Future studies should establish improved material characterization, preprocessing and quality-control procedures, while also considering regional availability and transportation requirements. This would enable more reliable comparison of sustainable materials across different geographical and infrastructure contexts.

9.3 Standardization and Industry Adoption

Another important gap is the transition from research-scale development to standardized engineering practice. Some emerging material systems require further validation before they can be routinely incorporated into structural design, specifications and construction practices.

Future work should focus on developing reliable performance criteria, design guidance and quality-control procedures supported by field evidence. Collaboration among research institutions, material producers, designers, contractors and regulatory organizations will be important for accelerating practical adoption.

9.4 Future Experimental and Scale-Up Research

Future research should validate the PDCLC framework using traceable experimental and field datasets covering mechanical performance, durability, embodied carbon and life-cycle cost. Larger-scale trials should examine material production, constructability, supply-chain requirements and performance under realistic infrastructure conditions. The framework can also be extended through sensitivity and uncertainty analysis, particularly for material replacement levels, emission factors, service life, discount rates and PDCLC weighting assumptions. This would determine how changes in key assumptions affect the final Sustainability Index and material ranking.

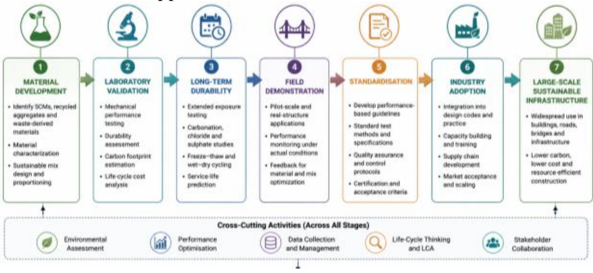


Figure 22. Future Research and Implementation Roadmap

Conclusion

Key Findings and Research Contribution

This study developed an integrated Performance–Durability–Carbon–Life-Cycle Cost (PDCLC) framework for the comparative assessment of conventional and sustainable construction material systems. The framework evaluates Conventional Concrete (CC), SCM-Based Concrete (SCM), Recycled Aggregate Concrete (RAC), Waste-Derived Concrete (WDC), and Alternative Binder Concrete (ABC) using four interconnected sustainability dimensions. The assessment demonstrates that sustainable material selection should not be based on a single criterion such as compressive strength, embodied carbon or initial cost. Instead, mechanical performance and durability must be considered together with environmental and whole-life economic performance. SCMs, recycled aggregates, waste-derived materials and alternative binders provide different sustainability advantages, but their suitability depends on material characteristics, mixture design, processing requirements and intended infrastructure application. The principal research contribution is the integration of these competing criteria into a single Sustainability Index (SI) using the study-specific weighting structure: $SI = 0.30P_N + 0.25P_N + 0.25C_N + 0.20L_N$ The framework assigns 30% to mechanical performance, 25% to durability, 25% to embodied-carbon performance and 20% to life-cycle cost, thereby maintaining engineering reliability as the primary requirement while incorporating environmental and economic considerations. Overall, the proposed PDCLC framework provides a transparent and systematic decision-support approach for comparing sustainable construction materials and identifying balanced solutions for future infrastructure. Its key contribution lies in linking technical reliability, long-term durability, carbon reduction and economic feasibility within one consistent material-selection framework.

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