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Sustainable Concrete Practices for Reducing Environmental Impact in Construction Industry

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ABSTRACT: *Concrete is fundamental to building and civil engineering infrastructure; however, its extensive use has resulted in significant environmental impacts, largely attributable to Portland cement production and intensive resource consumption. In response, sustainable concrete practices, including the incorporation of supplementary cementitious materials, recycled aggregates, and alternative binders, have been widely proposed as mitigation strategies. Despite this growing body of research, sustainability assessments remain predominantly carbon-centric and are frequently disconnected from the long-term performance requirements that govern structural engineering practice. This paper presents a critical review of sustainable concrete technologies, examining both their environmental justification and their engineering viability. The review demonstrates that an overreliance on embodied carbon metrics and simplified life cycle assessment frameworks often obscures the influence of durability, service life, and degradation mechanisms on cumulative environmental performance. While supplementary cementitious materials offer measurable reductions in initial emissions, their effectiveness is strongly dependent on material chemistry, curing conditions, and exposure environments. Similarly, recycled aggregate concrete aligns with circular economy objectives but exhibits persistent mechanical and durability limitations that constrain its application in long-life structural systems without rigorous quality control and performance-based design. The study further identifies methodological inconsistencies in life cycle assessment practice, particularly in system boundary definition and functional unit selection, as a major barrier to meaningful comparison between conventional and sustainable concrete systems. It is concluded that credible sustainability evaluation must extend beyond material substitution and emission reduction to incorporate durability-informed, performance-based life cycle frameworks capable of supporting reliable engineering decision-making.*

KEYWORDS: *Sustainable concrete; Supplementary cementitious materials; Recycled aggregates; Life cycle assessment; Circular economy.*

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1. Introduction

Concrete is the most widely consumed construction material globally and remains fundamental to both building engineering and civil infrastructure systems. Its dominance is driven by its versatility, durability, availability of raw materials, and cost efficiency. However, this ubiquity has resulted in a substantial environmental burden, primarily due to the production of Portland cement, which is responsible for approximately 7–8% of global anthropogenic carbon dioxide (CO_2) emissions (Andrew, 2018; Scrivener, John, & Gartner, 2018). The environmental implications of concrete extend beyond greenhouse gas emissions to include high energy consumption, depletion of natural resources, and generation of construction and demolition waste.The urgency of mitigating climate change has intensified scholarly and industrial interest in sustainable concrete technologies. Nevertheless, the existing body of literature reveals a persistent imbalance between environmental performance claims and structural engineering requirements. Many studies emphasize reductions in embodied carbon without adequately addressing durability, service life, constructability, and long-term performance, which are central concerns in both building and civil engineering practice. Consequently, there is a growing recognition that sustainability in concrete must be evaluated through an integrated framework that accounts for environmental impact, mechanical performance, and life-cycle behavior.

This literature review critically examines sustainable concrete practices with a focus on supplementary cementitious materials, recycled aggregates, alternative binders, and life cycle assessment methodologies. Emphasis is placed on identifying trade-offs, methodological limitations, and research gaps that constrain the practical adoption of sustainable concrete in real engineering applications.

2. Sustainability in Concrete Engineering: Conceptual and Methodological Perspectives

2.1 Limitations of Carbon-Centric Approaches

A prevailing weakness in contemporary sustainable concrete research is the disproportionate emphasis placed on embodied CO_2 as the dominant, and often exclusive, indicator of sustainability. Although carbon emissions constitute a central environmental concern, the widespread reliance on carbon-centric metrics reflects a reductive interpretation of sustainability that obscures critical performance-related consequences (Habert et al., 2020; Miller, Horvath, & Monteiro, 2016). Such approaches implicitly assume that reductions in initial emissions translate directly into long-term environmental benefits, an assumption that is rarely interrogated in a rigorous engineering context. In reality, concrete structures—particularly those forming civil infrastructure—are designed to perform over service lives exceeding 50 to 100 years, during which durability governs environmental performance far more decisively than initial material impacts.

Low-carbon concrete formulations that achieve emission reductions at the production stage may inadvertently introduce vulnerabilities to degradation mechanisms such as chloride ingress, carbonation, and sulfate attack. When these mechanisms are insufficiently controlled, the resulting loss of durability accelerates maintenance demands, repair interventions, and, in extreme cases, premature replacement, thereby amplifying cumulative life-cycle impacts (Alexander & Thomas, 2015; Neville, 2011). Consequently, sustainability assessments that fail to explicitly incorporate durability performance and degradation mechanisms risk systematically overstating the environmental merits of low-carbon concretes. This methodological shortcoming not only undermines the credibility of sustainability claims but also highlights a fundamental disconnect between environmental assessment practices and the long-term performance expectations that govern structural design in civil and building engineering.Table 1 summarizes the key weaknesses in contemporary sustainable concrete research, highlighting the overemphasis on embodied CO_2, assumptions about long-term benefits, durability vulnerabilities, and methodological shortcomings. It links each issue to its engineering and environmental implications, supported by relevant literature.

Table 1: Critical Analysis of Limitations in Carbon-Centric Sustainable Concrete Assessments

Aspect	Issue	Implications	References
Embodied CO_2 focus	Carbon-centric	Overstates sustainability	Habert et al., 2020; Miller et al., 2016
Assumed benefit	Initial emissions ≈ long-term benefit	Misleads environmental claims	Habert et al., 2020; Miller et al., 2016
Durability	Susceptible to chloride, carbonation, sulfate	Accelerated maintenance, repair	Alexander & Thomas, 2015; Neville, 2011
Methodology	Ignores degradation	Disconnect with structural performance	Alexander & Thomas, 2015; Neville, 2011

2.2 Life Cycle Assessment and Functional Units

Life Cycle Assessment (LCA) has emerged as the dominant framework for quantifying the environmental impacts of concrete; however, its widespread application has not been matched by methodological rigor or conceptual consistency. A substantial body of literature demonstrates that LCA outcomes for concrete are highly contingent on subjective methodological choices, particularly those related to system boundaries, allocation rules, and functional unit definition (Habert et al., 2011; Müller et al., 2014). Despite this sensitivity, many studies adopt simplified cradle-to-gate system boundaries that exclude the use phase and end-of-life, thereby neglecting the decisive influence of service life, maintenance, and durability on cumulative environmental performance.

Of particular concern is the persistent use of inadequate functional units, most notably the normalization of impacts per cubic meter of concrete. Such an approach implicitly assumes material equivalence and disregards structural function, load-bearing capacity, and longevity, rendering comparisons between conventional and "sustainable" concretes fundamentally flawed (Habert & Roussel, 2009). This methodological deficiency systematically biases result in favor of low-binder or low-carbon mixtures without accounting for potential performance penalties over time. Consequently, the lack of performance-based functional units remains a critical barrier to the meaningful evaluation, comparison, and validation of sustainable concrete systems within both building and civil engineering contexts.The diagram in Fig. 1 illustrates a cyclical loop of challenges in Life Cycle Assessments for concrete, including inconsistent methodologies, inappropriate functional units, inaccurate comparisons, hindered validation, and the need for performance-based units, perpetuating difficulties in sustainable evaluations.

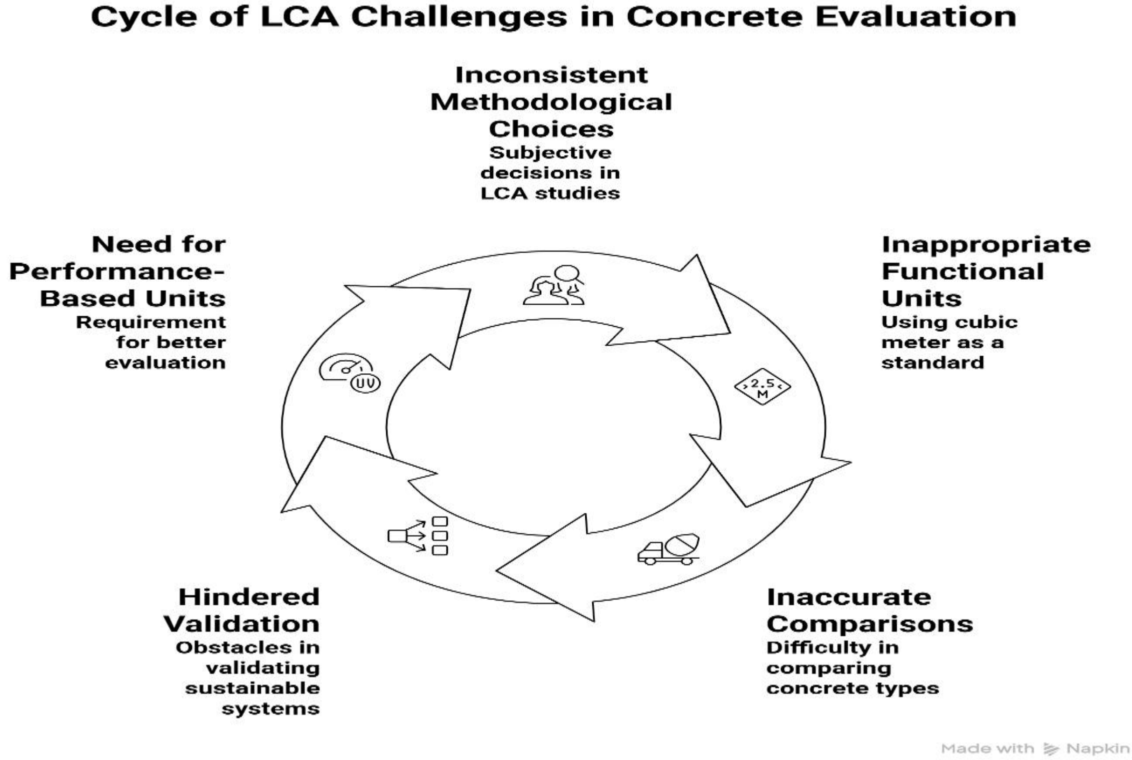

Fig. 1: Cycle of LCA Challenges in Concrete Evaluation

3. Supplementary Cementitious Materials: Environmental Benefits and Engineering Constraints

3.1 Environmental Performance of SCMs

The partial replacement of Portland cement with supplementary cementitious materials (SCMs) represents the most mature and widely implemented strategy for reducing the environmental impact of concrete. Common SCMs include fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, and calcined clays. Numerous life cycle assessment (LCA) studies report embodied CO_2 reductions ranging from 20% to over 60%, depending on replacement level, SCM chemistry, and system boundary assumptions (Scrivener et al., 2018; Miller et al., 2016). While these reductions are frequently cited as evidence of sustainability, they often rest on generalized material substitution ratios that overlook compositional variability and performance implications.

Recent material characterization studies have demonstrated that the oxide composition and mineralogical variability of alternative and waste-derived materials can significantly influence their reactivity and environmental effectiveness when used in cementitious systems (Tiza, Okafor, & Agunwamba, 2024; Nsobundu & Tiza, 2025). These findings challenge the implicit assumption, common in LCA-driven studies, that SCMs are environmentally interchangeable solely on the basis of mass replacement. Instead, they suggest that sustainability outcomes are strongly conditioned by material chemistry, processing history, and compatibility with the cement matrix.

Calcined clays, particularly in limestone calcined clay cement (LC^3) systems, have attracted significant attention due to their global availability and compatibility with existing cement production infrastructure (Scrivener et al., 2018). While LC^3 systems offer meaningful emission reductions without reliance on declining industrial by-products, their environmental superiority remains contingent on controlled calcination processes, optimized mix design, and region-specific material availability. Consequently, the environmental performance of SCM-based systems cannot be generalized without careful consideration of material provenance and engineering context.

3.2 Mechanical Performance and Durability Considerations

Despite their environmental advantages, SCMs introduce significant engineering constraints that are frequently underemphasized in sustainability-focused literature. High replacement levels of fly ash or slag are well documented to delay early-age strength development, with direct implications for construction sequencing, formwork stripping, and early load application (Thomas, 2013). These effects are not merely operational inconveniences but can influence structural safety margins and project economics if not explicitly addressed. Moreover, the performance of SCM-based concretes is highly sensitive to curing regimes. Experimental evidence shows that inadequate curing can negate anticipated durability benefits, particularly in aggressive exposure conditions (Alexander, Bentz, & De Belie, 2012). Statistical and probabilistic modeling studies further demonstrate that mixture proportioning plays a decisive role in balancing strength development, durability, and sustainability objectives, underscoring the inadequacy of prescriptive replacement approaches (Agunwamba, Okafor, & Tiza, 2024; Agunwamba, Tiza, & Okafor, 2024).

While SCMs generally enhance resistance to chloride ingress and sulfate attack, their performance with respect to carbonation remains inconsistent, especially in blended systems with reduced clinker content (Alexander & Thomas, 2015). This inconsistency is particularly critical for reinforced concrete structures, where accelerated carbonation directly compromises steel passivation. Studies evaluating reclaimed and waste-derived aggregates in cement concrete further indicate that material heterogeneity can exacerbate permeability-related durability risks if not rigorously controlled (Tiza, Agunwamba, & Okafor, 2024). Collectively, these findings reinforce the argument that SCM utilization must be guided by performance-based mix design, exposure-specific durability assessment, and statistically informed optimization, rather than by generalized sustainability narratives. Without such rigor, the environmental benefits attributed to SCMs risk being overstated and potentially offset by long-term durability penalties.Table 2 summarizes the main environmental and engineering considerations of SCMs in sustainable concrete using short, precise keywords and phrases.

Table 2: Key Environmental and Engineering Considerations of Supplementary Cementitious Materials (SCMs)

Aspect	Issue / Limitation	Implications	References
CO_2 reduction	Depends on SCM type & replacement	Sustainability variable	Scrivener et al., 2018; Miller et al., 2016
Material variability	Oxide/mineral differences	Reactivity & emissions inconsistent	Tiza, Okafor, & Agunwamba, 2024; Nsobundu & Tiza, 2025
LC^3 systems	Process & availability dependent	Conditional environmental benefits	Scrivener et al., 2018
Early-age strength	High fly ash/slag	Delayed strength, construction impact	Thomas, 2013
Curing	Inadequate	Reduced durability	Alexander, Bentz, & De Belie, 2012
Mix proportioning	Prescriptive replacement	Needs performance-based optimization	Agunwamba, Okafor, & Tiza, 2024; Agunwamba, Tiza, & Okafor, 2024
Carbonation resistance	Inconsistent in low-clinker mixes	Reinforcement corrosion risk	Alexander & Thomas, 2015
Material heterogeneity	Reclaimed/waste SCMs	Increased permeability & durability risk	Tiza, Agunwamba, & Okafor, 2024

4. Recycled Aggregate Concrete and Circular Economy Aspirations

4.1 Environmental Rationale

The use of recycled concrete aggregates (RCA) is frequently promoted as a cornerstone of circular economy strategies in construction, primarily due to its potential to reduce dependence on virgin aggregates and divert construction and demolition waste from landfills. Life cycle studies indicate that, when RCA is sourced locally, reductions in resource depletion and transportation-related emissions can be achieved relative to conventional aggregate supply chains (Blengini& Garbarino, 2010; Tam, Tam, & Wang, 2007). However, these reported benefits are highly contingent on contextual factors such as hauling distance, processing intensity, and material quality.

A critical limitation of much of the existing literature is its tendency to frame RCA utilization as inherently sustainable, without sufficiently interrogating the material heterogeneity and compositional variability that characterize recycled aggregates. Detailed material characterization studies demonstrate that recycled aggregates derived from heterogeneous waste streams exhibit significant variability in oxide composition, residual binder content, and contaminant presence, all of which influence their environmental and engineering performance (Tiza, Okafor, & Agunwamba, 2024; Nsobundu & Tiza, 2025). These findings challenge the assumption that RCA can be treated as a direct, environmentally neutral substitute for natural aggregates in sustainability assessments.

Consequently, the environmental rationale for RCA must be evaluated within a performance-sensitive framework that accounts for material processing requirements, quality control measures, and the downstream implications for concrete durability and service life.

4.2 Structural and Durability Limitations

Despite their environmental appeal, recycled aggregate concretes consistently exhibit inferior mechanical performance compared to concretes produced with natural aggregates. Experimental investigations report systematic reductions in compressive strength, elastic modulus, and abrasion resistance, primarily attributed to the presence of adhered mortar, increased porosity, and weaker interfacial transition zones (de Juan & Gutiérrez, 2009; Poon et al., 2004). These deficiencies are not merely material inconveniences but have direct implications for structural reliability and design safety margins. Durability concerns are particularly acute. Increased permeability associated with RCA concretes accelerates carbonation and chloride ingress, thereby heightening the risk of reinforcement corrosion, especially in aggressive exposure environments (Poon et al., 2004). Evaluations of reclaimed construction materials, including reclaimed asphalt pavement used as coarse aggregates, further indicate that uncontrolled incorporation of waste-derived aggregates can exacerbate durability-related deterioration mechanisms if compositional and microstructural characteristics are not rigorously managed (Tiza, Agunwamba, & Okafor, 2024).

While advanced mix optimization and statistical modeling approaches have shown potential in mitigating some of these performance penalties, their effectiveness is highly dependent on stringent quality control and material pre-treatment (Agunwamba, Okafor, & Tiza, 2024). In the absence of such controls, the structural and durability limitations of RCA significantly constrain its application in load-bearing and long-life infrastructure systems.

Taken together, these findings suggest that the sustainability of RCA concrete cannot be presumed on the basis of waste diversion alone. Without performance-based specifications and durability-informed design, the environmental benefits associated with recycled aggregates risk being offset by reduced service life and increased maintenance demands, undermining the fundamental objectives of circular construction. Table 3 highlights thekey environmental and engineering considerations of RCA concrete**.** It focuses onperformance variability, mechanical and durability limitations, material heterogeneity, and the importance of quality control**.** Each issue is linked to practical implications for structural performance and sustainability, supported by relevant literature.

Table 3: Environmental and Engineering Considerations of Recycled Aggregate Concrete (RCA)

Aspect	Issue / Limitation	Implications	References
Environmental rationale	Local sourcing, hauling distance, processing	Variable CO_2 reduction, resource savings	Blengini& Garbarino, 2010; Tam, Tam, & Wang, 2007
Material variability	Oxide composition, residual binder, contaminants	Performance & sustainability inconsistent	Tiza, Okafor, & Agunwamba, 2024; Nsobundu & Tiza, 2025
Mechanical performance	Reduced strength, modulus, abrasion	Limits structural reliability	de Juan & Gutiérrez, 2009; Poon et al., 2004
Durability	Increased permeability, carbonation, chloride ingress	Reinforcement corrosion risk	Poon et al., 2004
Reclaimed materials	RCA & RAP heterogeneity	Accelerated deterioration if uncontrolled	Tiza, Agunwamba, & Okafor, 2024
Quality control	Need for mix optimization, pre-treatment	Essential for structural and durability performance	Agunwamba, Okafor, & Tiza, 2024
Circular economy assumption	Waste diversion ≠ guaranteed sustainability	Environmental benefits may be offset by maintenance & short service life	Blengini& Garbarino, 2010; Tam, Tam, & Wang, 2007

5. Alternative Binders and Emerging Low-Carbon Technologies

5.1 Alkali-Activated and Geopolymer Concretes

Alkali-activated materials (AAMs) and geopolymers have been proposed as radical alternatives to Portland cement, offering potential emission reductions of up to 80% (Provis & van Deventer, 2014). However, their environmental superiority is not unequivocal. The production of alkaline activators, particularly sodium silicate, contributes significantly to environmental burdens (Habert et al., 2011). Moreover, the lack of standardized design codes, long-term durability data, and field-scale

performance evidence remains a major barrier to adoption in mainstream civil and building engineering practice.

5.2 Carbonation and CO_2-Curing Technologies

Carbonation curing technologies aim to sequester CO_2 during early curing stages, partially offsetting emissions from cement production (Monkman & MacDonald, 2017). While technically promising, the overall carbon uptake remains modest relative to total cement emissions, and practical implementation is currently limited to precast applications.

6. Integration of Building and Civil Engineering Perspectives

A notable weakness in the literature is the fragmentation between building-focused and infrastructure-focused sustainability research. Building engineering studies often prioritize operational energy efficiency, whereas civil engineering research emphasizes durability and structural reliability. However, embodied emissions dominate infrastructure projects, while life-cycle interactions dominate buildings (Pomponi &Moncaster, 2017).

Sustainable concrete strategies must therefore be evaluated within integrated frameworks that account for structural performance, environmental impact, and service life across both disciplines.

7. Research Gaps and Future Directions

Despite substantial progress, several critical gaps remain:

1. Lack of standardized, performance-based sustainability metrics.
2. Insufficient long-term field data for low-carbon concrete systems.
3. Limited integration of durability modeling into LCA frameworks.
4. Inadequate alignment between sustainability research and design codes.

Addressing these gaps is essential for translating laboratory-scale innovations into robust engineering solutions.

8. Conclusions

Sustainable concrete practices offer significant potential for reducing the environmental impact of building and civil engineering projects. However, sustainability cannot be evaluated solely on the basis of reduced embodied carbon. Durable performance, service life, and structural reliability must remain central considerations. Future research should prioritize integrated, performance-driven sustainability frameworks capable of informing both engineering practice and policy development.

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