Development Trends and Applications of Environmentally Friendly Building Materials

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Abstract. The construction industry is a major contributor to global CO_2 emissions, primarily due to the production of Ordinary Portland Cement (OPC) and the extensive use of virgin aggregates. This study synthesizes recent progress on environmentally friendly building materials, focusing on three main alternatives: low-carbon cements, recycled aggregate concrete (RAC), and geopolymers. Harmonized metrics—CO_2 emissions per unit volume (kg CO_2-eq/m^3) and emissions per unit strength (kg CO_2-eq/MPa)—are applied to compare these materials in terms of embodied carbon, compressive strength, and durability. Findings indicate that blended cements can achieve 30–60% CO_2 reduction while maintaining mechanical and durability performance comparable to OPC. RAC offers modest reductions (10–20%) but is constrained by strength and durability limitations, restricting its structural applications. Geopolymers show the greatest theoretical emission reduction (30–70%), though their performance varies widely and adoption is hindered by gaps in standardization. Overall, blended cements appear to be the most practical short-term solution, while geopolymers hold significant potential for future development with further research and codification.

Keywords: Building, materials, low-carbon cements, LCA.

1. Introduction

1.1. Background and Content

Over the last two decades, the construction and building sector has been one of the largest global sources of greenhouse gas emissions, due to the combination of operational energy (heating/cooling) with embodied emissions from material manufacturing processes [1-4]. Within the embodied impacts, cement dominates the concrete footprint [5-6]. A typical Ordinary Portland Cement (OPC) production emits 0.75–0.90 t CO_2 per ton of cement, with ~50% from limestone calcination ($CaCO_3 \rightarrow CaO + CO_2$), ~35–40% from kiln fuel and electricity, and the remainder from quarrying, transport, and grinding [7]. As cement output increased to around 4 Gt yr^{-1} during the 2000s–2010s, its global share (~7–8%) of CO_2 emissions has received significant attention [5].

Concrete's natural aggregates (sand, gravel, crushed stone) typically make up around 60–75% of the concrete volume [1]. Although aggregates emit far less CO_2 per ton compared to cement, their large consumption volumes and transport distances contribute significantly to embodied carbon and ecological pressures [2,8].

While not the primary focus of this paper, reinforcement steel also contributes significantly to global CO_2 emissions—around 7–9% of the total. The production route determines intensity, from BF–BOF ≈ 2.33 t CO_2/t to DRI–EAF ≈ 1.37 t CO_2/t, and scrap–EAF ≈ 0.68 t CO_2/t. This underscores that binder, aggregate, and reinforcement choices together set the whole-system impact [9].

1.2. Gap

Despite a fast-growing literature on eco-friendly materials, comparative studies are rare. Key issues include: (i) performance comparability—compressive and tensile strength, early and long-term behavior, and durability evidence (freeze–thaw, chloride ingress, carbonation) versus OPC benchmarks; and (ii) inconsistencies in life-cycle assessment (LCA) scope and functional units—such as reporting per ton or per cubic meter for mixes of different strength groups—that hinder fair comparison [2,3,5,6].

1.3. Objective & Significance

This review aims to identify the dominant embodied carbon levels in conventional concrete (OPC and virgin aggregates) and summarize them within a 10–20 year context; compare eco-friendly alternatives such as low-carbon cements, recycled aggregates, and geopolymers in terms of compressive strength (MPa), durability indicators, and embodied CO_2; quantify and visualize differences using harmonized units—kg CO_2-eq/m³ and kg CO_2-eq/MPa; and evaluate near-term feasibility with respect to applications, code or specification gaps, and regional applicability [4-7]. The significance of this study lies in providing a functional framework (e.g., kg CO_2/MPa) that engineers and policymakers can directly apply, while also mapping research versus practice gaps to accelerate the safe adoption of lower-carbon materials [2,3].

1.4. Eco-Friendly Building Material Background

This study focuses on materials that can materially reduce embodied CO_2 in mainstream concrete: low-carbon cements (OPC blends and clinker-efficient systems), recycled aggregate concrete (RAC), and geopolymers (alkali-activated binders). Each addresses a different mechanism—reducing clinker, reducing virgin aggregates, or replacing OPC chemistry [2,5,6].

1.4.1. Low-carbon cements (OPC blends, clinker-efficient systems)

Mechanism. Partial clinker replacement with supplementary cementitious materials (SCMs)—such as fly ash, GGBS, and calcined clay/limestone (LC³)—combined with improved fuels and efficiency. OPC emits around 0.75–0.90 t CO_2/t, with 50% from calcination and ~35–40% from energy use, so cutting clinker directly reduces emissions [4,6].

Pros. Uses existing cement plants and standard pathways. Achieves significant per-m³ CO_2 reductions while maintaining target strengths when properly designed. Leverages industrial by-products [5,6].

Cons. SCM availability varies regionally. Early-age strength may be slower, and durability outcomes depend on mix design and curing. Consistent functional-unit reporting is needed for fair comparisons across strength classes [2,5].

1.4.2. Recycled-aggregate concrete (RAC)

Mechanism. Replaces a portion of natural aggregates (60–75% of concrete volume) with recycled concrete or masonry aggregates, reducing virgin extraction and transport impacts [1,2].

Pros. Reduces natural resource consumption and landfill waste. Suitable for non-structural and some structural applications, provided appropriate grading, pre-treatment, or beneficiation is applied. Significant embodied carbon reduction is possible where virgin aggregates require long-distance transport [2,3].

Cons. Higher water absorption and variability can reduce workability and strength if unmanaged. Durability is mixed and source-dependent. Design-code allowances for high replacement ratios remain limited in some jurisdictions [2,3].

1.4.3. Geopolymers / alkali-activated binders

Mechanism. OPC-free binders formed by alkali activation of aluminosilicate sources (e.g., fly ash, slag, metakaolin), offering large potential CO_2 reductions by avoiding clinker. Strengths can be tailored via precursor choice, activator concentration, and curing regime [6].

Pros. Typically achieve 30–70% lower embodied CO_2 emissions than OPC mixes. With proper curing and mix design, structural strength can be realized, while utilizing industrial by-products [5].

Cons. Standards and long-term testing remain limited. Performance is sensitive to precursor chemistry, activator choice, and curing conditions (temperature, humidity). Supply chains for consistent precursors vary regionally [2,6].

2. Result

2.1. Background

The results synthesized published data on environmentally friendly concretes and compared them against the OPC benchmark. To ensure comparability, metrics were standardized to embodied emissions per unit volume (kg CO_2-eq/m^3) and emissions normalized to compressive strength (kg CO_2-eq/MPa). The analysis focused on three key aspects: carbon emissions, mechanical performance, and durability.

2.2. CO_2 Emissions

OPC production remains the highest-carbon option, with embodied emissions of ~750–900 kg CO_2/t cement, translating to ~850–950 kg CO_2/m^3 of C30–C40 concrete [4–6]. Blended cements containing GGBS, fly ash, or LC^3 typically achieve 30–60% lower emissions per cubic meter, depending on clinker substitution level [5]. Geopolymers demonstrate the greatest theoretical reduction (30–70% lower than OPC), though their performance varies significantly with precursor and activator chemistry [2,5]. RAC provides more modest reductions (~10–20%), with the largest gains in contexts where virgin aggregates are transported over long distances [3].

Table 1. Reported CO_2 emissions of different concretes

Material system	Reported emissions (kg CO_2-eq/m^3)	Relative reduction vs OPC	Sources
OPC (C30–C40 baseline)	~850–950	—	Chen et al. (2010); IEA (2018); Naqi & Jang (2019)
Blended cements (GGBS, Fly ash, LC^3)	~350–600	30–60% lower	Maddalena et al. (2018)
Geopolymers	~250–600	30–70% lower	Abera (2024); Maddalena et al. (2018)
RAC (>30% replacement)	~700–800	10–20% lower	Girya et al. (2021); Abera (2024)

As shown in Table 1, OPC mixes have the highest embodied emissions, while blended cements consistently achieve substantial reductions. Geopolymers show the lowest reported values but also the widest variability, reflecting sensitivity to precursor and activator chemistry. RAC demonstrates only modest reductions, highlighting its role as a supplementary rather than transformative strategy.

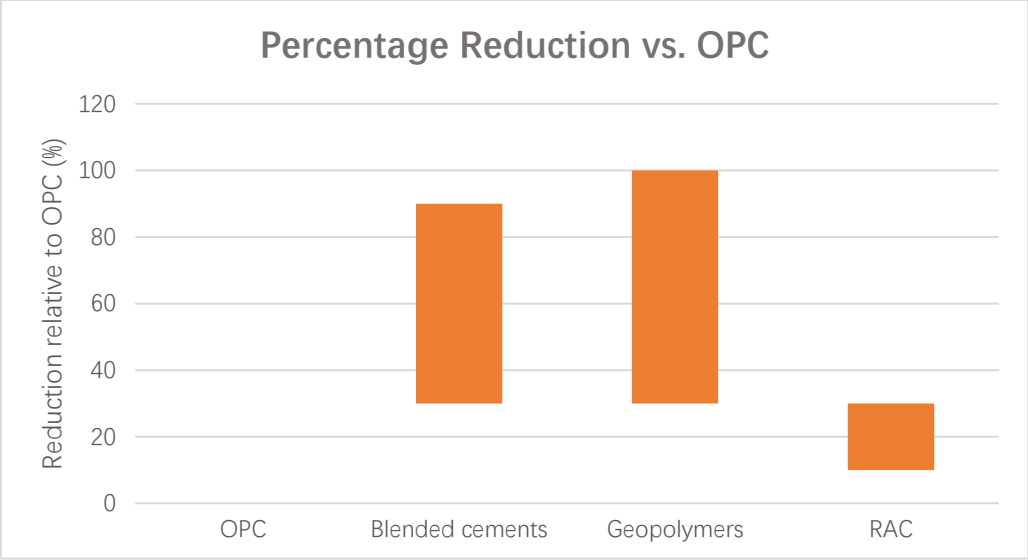


Fig. 1 Percentage reduction in CO_2 emissions compared with OPC

Figure 1 confirms that blended cements and geopolymers provide significant carbon savings, while RAC achieves only limited reductions. However, the variability in geopolymer results emphasizes the need for standardized production and testing.

2.3. Compressive Strength (Mechanical Performance)

OPC concretes typically achieve 28-day compressive strength of ~30–60 MPa (C30–C60). Blended cements, such as LC^3 and slag/fly ash systems, generally reach comparable long-term strength (25–50 MPa), though early-age strength gain is slower [6]. RAC usually experiences a 10–25% strength loss at high replacement ratios, but pre-treatment or admixtures can mitigate this reduction [3]. Geopolymer concretes show the widest strength range (20–80 MPa), with performance highly dependent on curing regime and precursor composition [5].

Table 2. Reported compressive strength ranges of different concretes

Material system	REPORTED RANGE	NOTES
OPC (baseline)	~30-60	C30–C60 concrete; standard mixes at 28 days.
Blended cements (GGBS, Fly ash, LC^3)	~25-50	Comparable long-term strength; slower early-age gain.
Geopolymers	~20-80	Strength reduction at high replacement ratios; can be improved with treatment/admixtures.
RECYCLED AGGREGATE CONCRETE (RAC)	~20-45(10-25% lower than OPC)	Highly dependent on precursor type, activator, and curing.

As seen in Table 2, OPC remains the benchmark for reliable compressive strength. Blended cements show similar performance in the long term, geopolymers can achieve both low and very high values depending on formulation, and RAC generally lags behind unless treated.

2.4. Durability Indicators

Durability is a critical factor that determines service life and the actual carbon reduction potential, since a longer service life reduces the need for material replacement.

Table 3. Comparison on durability of OPC and eco friendly concretes across key indicators.

Material system	Chloride penetration resistance	Carbonation depth	Freeze–thaw resistance	Notes
OPC (baseline)	Moderate	Baseline	>90% strength after 300 cycles	Standard benchmark.
Blended cements	Lower (improved)	Similar/lower	>90% strength after 300 cycles	Improved durability in aggressive environments.
RAC	Higher (worse)	Higher (worse)	Variable; requires treatment	Durability depends on aggregate quality and replacement ratio.
Geopolymers	Lower (improved)	Variable	Variable; curing-sensitive	Strong chloride resistance but mixed freeze–thaw performance.

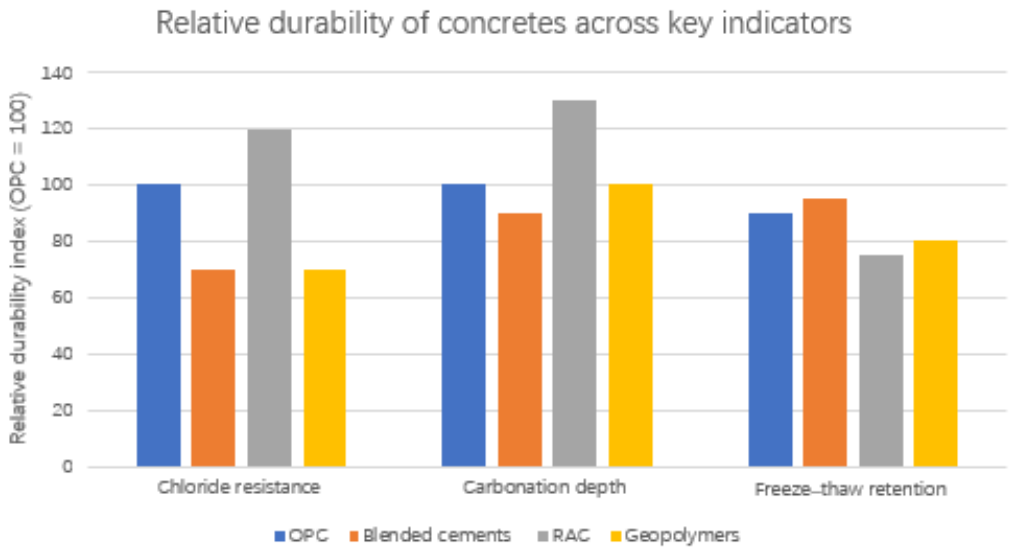


Fig. 2 Relative durability indices (normalized to OPC = 100)

The data in Table 3 show that blended cements generally provide superior durability compared to OPC, especially in aggressive environments. RAC, however, exhibits weaker durability, particularly in carbonation resistance. Geopolymers excel in chloride resistance but their freeze–thaw performance remains inconsistent.

Figure 2 highlights the improvements of blended cements in chloride and freeze–thaw resistance, while RAC falls short of the baseline. Geopolymers demonstrate potential advantages but show inconsistent performance across durability measures.

2.5. Trade-Off Synthesis

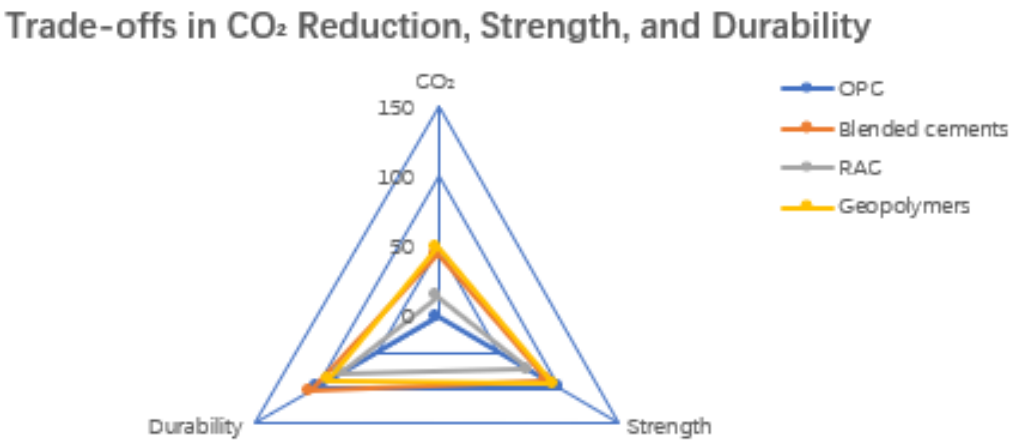


Fig. 3 Multi-axis radar chart comparing trade-offs in CO_2 reduction, compressive strength, and durability.

As shown in Figure 3, OPC maintains strong performance in strength and durability but offers no emissions reduction. Blended cements achieve a balanced outcome across all axes, combining substantial carbon savings with reliable strength and durability. RAC demonstrates modest emissions reduction but consistently underperforms in strength and durability. Geopolymers show excellent emissions reduction potential but uncertain strength and durability, underscoring the need for further standardization.

2.6. Findings

Overall, OPC remains the most reliable material in terms of strength and durability, but also has the highest embodied carbon emissions. Blended cements (LC^3, GGBS, fly ash) represent the most balanced solution, combining significant emissions reduction with strong performance and

established adoption pathways. RAC provides environmental benefits through aggregate recycling but suffers from lower strength and durability, restricting it mainly to non-structural applications unless improved by treatment. Geopolymers offer the greatest theoretical potential for decarbonization, yet their variable performance, reliance on precursor supply, and lack of standardization limit widespread adoption at present.

3. Conclusion

This study has demonstrated that Ordinary Portland Cement (OPC) remains the global benchmark for compressive strength and durability but is also the most carbon-intensive option, contributing significantly to global CO_2 emissions. By contrast, eco-friendly alternatives—blended cements, recycled aggregate concrete (RAC), and geopolymers—show varying potential in reducing embodied carbon. Blended cements achieve 30–60% reductions while maintaining comparable mechanical and durability performance; RAC offers modest savings of 10–20% but is limited by reduced strength and inconsistent durability; geopolymers demonstrate the highest theoretical reduction of 30–70%, though their performance remains highly variable.

Despite these advancements, current eco-friendly concretes face notable challenges. Blended cements depend on the regional availability of supplementary cementitious materials, and their early-age strength is often lower than OPC. RAC suffers from poor mechanical and durability properties when used at high replacement levels, restricting its role to non-structural applications. Geopolymers, while promising, lack standardized specifications and consistent supply chains, and their durability under varied curing and environmental conditions is not yet fully verified.

Looking ahead, the sustainable transition of the construction industry will require a combined strategy. In the short term, blended cements should be prioritized due to their proven balance of performance and reduced emissions, supported by existing standards. In the long term, research and policy should focus on advancing geopolymers, with emphasis on standardization, large-scale field trials, and supply chain development. Improvements in RAC treatment technologies may also broaden its applicability. Ultimately, integrating technological innovation with regulatory support will be essential to accelerate the adoption of low-carbon building materials and achieve meaningful reductions in the construction sector’s carbon footprint.

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