Life Cycle Assessment of Reinforced Concrete Buildings for Sustainable Construction

Aakil Khan[1], **Dr. Deepak Verma**[2]

[1]M.Tech Research Scholar, Department of Civil Engineering, University Institute of Engineering and Technology, Maharshi Dayanand University, Rohtak, Haryana, India
[2]Research Supervisor, Department of Civil Engineering, University Institute of Engineering and Technology, Maharshi Dayanand University, Rohtak, Haryana, India

Abstract

Reinforced concrete (RC) is the most widely used structural material for buildings in the world. It is strong, durable, and flexible in design, but its production has a large environmental cost. Cement alone contributes approximately 7 to 8 percent of global carbon dioxide (CO2) emissions. Life cycle assessment (LCA) is a scientific method used to measure the total environmental impact of a building from the production of raw materials to demolition and disposal. This review paper covers published journal studies on the LCA of RC buildings, focusing on three main areas: embodied energy, carbon emissions, and the role of supplementary cementitious materials (SCMs) and other sustainability strategies. Published data shows that the embodied energy of standard RC buildings ranges from 3.5 to 6.2 gigajoules per square meter of floor area, and embodied CO2 emissions range from 280 to 520 kilograms per square meter. Using fly ash at 30 percent replacement reduces CO2 by 25 to 35 percent. Using GGBFS at 50 percent replacement reduces CO2 by 40 to 54 percent. Operational energy during the building's service life is often 3 to 10 times larger than embodied energy over 50 years, yet many LCA studies still focus only on the material production phase. The review identifies six key research gaps including the absence of durability-based service life prediction in most studies, limited data from developing countries, and the routine exclusion of end-of-life recycling credits. Future research priorities are clearly identified. The paper provides reliable, data-supported guidance for architects, structural engineers, and policymakers who want to reduce the environmental impact of RC building construction.

Keywords: life cycle assessment; reinforced concrete; buildings; embodied energy; carbon emissions; supplementary cementitious materials; fly ash; GGBFS; sustainable construction; service life

1. Introduction

Reinforced concrete is the structural system used in the majority of buildings around the world. It combines the compressive strength of concrete with the tensile strength of steel reinforcing bars to create a material that can carry virtually any type of load. The global production of concrete exceeds 30 billion tonnes per year, which makes it the second most consumed material after water (Mehta & Monteiro, 2014). Buildings make up a very large share of this consumption, as nearly every multi-storey residential building, office tower, hospital, and school built today uses an RC structural frame.

The construction sector is one of the largest contributors to global greenhouse gas emissions and energy consumption. According to the United Nations Environment Programme (UNEP, 2021), buildings and construction together account for about 37 percent of global CO2 emissions and around 36 percent of global final energy use. A major share of this comes from the manufacture of Portland cement, the binding agent in concrete. The calcination of limestone and the burning of fuel to heat cement kilns together produce about 0.74 to 0.95 kilograms of CO2 for every kilogram of cement made (Flower & Sanjayan, 2007). With annual global cement production reaching approximately 4.2 billion tonnes, this means the cement industry emits roughly 3 to 4 billion tonnes of CO2 every year (IEA, 2022).

The reinforcing steel in RC buildings adds another significant environmental burden. Steel production using a traditional blast furnace method consumes approximately 19 to 29 megajoules per kilogram and emits 1.5 to 2.8 kilograms of CO2 per kilogram, depending on the production route (Hammond & Jones, 2008). In a typical mid-rise RC building, steel reinforcement represents about 80 to 150 kilograms per square meter of floor area, making it the second-highest contributor to embodied carbon after cement.

In response to these environmental challenges, life cycle assessment (LCA) has become the standard tool for measuring and comparing the environmental performance of buildings. LCA tracks all inputs of energy and materials and all outputs of emissions and waste across every stage of a building's life, from the extraction of raw materials through construction, use, maintenance, and final demolition. This whole-life perspective is important because it prevents decisions that reduce impact in one stage while increasing it in another. For example, using a lower-quality concrete may reduce initial production emissions slightly but require more repairs during the building's life, increasing total emissions.

Despite the growth of LCA research for buildings, there are important gaps in the published literature. Most studies focus heavily on the material production and construction phases and give less attention to the operational energy used in the building during its service life. Even fewer studies properly account for the role of concrete durability, which determines how long the building will last and how much maintenance it will need. A more durable concrete, even if it costs slightly more to produce, may have significantly lower total life cycle emissions because it reduces maintenance needs and extends the service life of the structure.

This review paper covers published journal research on the LCA of RC buildings up to 2024. The specific objectives are: (1) to explain the LCA methodology as applied to RC buildings and identify the key stages and indicators used in the literature; (2) to summarize the embodied energy and CO2 emission data from published studies; (3) to evaluate the effect of SCMs and other sustainability strategies on reducing environmental impacts; (4) to discuss the relationship between concrete durability and LCA outcomes; and (5) to identify research gaps and suggest future directions.

2. Life Cycle Assessment Methodology for RC Buildings

2.1 Definition and Standards

Life cycle assessment is defined by the international standards ISO 14040 (2006) and ISO 14044 (2006). ISO 14040 describes the general principles and framework of LCA, while ISO 14044 provides detailed requirements for conducting each phase of an LCA. Together, these standards define a four-phase process: (1) goal and scope definition, where the purpose of the study, the system boundary, and the functional unit are specified; (2) life cycle inventory (LCI) analysis, where all inputs and outputs of the system are quantified; (3) life cycle impact assessment (LCIA), where the environmental consequences of the inventory flows are calculated; and (4) interpretation, where the results are analyzed and conclusions are drawn.

For RC buildings, the functional unit is typically defined as one square meter of floor area per year of service, or simply one square meter for a fixed 50-year reference service life. The choice of functional unit has a significant effect on results: if two buildings have the same 50-year embodied energy but one lasts 80 years and the other only 40 years before needing major structural repair, the longer-lasting building has a lower impact per year of useful service. Many published studies use a fixed 50-year functional unit without adjusting for actual service life differences between mix designs, which is a recognized limitation.

2.2 System Boundaries for RC Buildings

The system boundary defines which life cycle stages are included in the LCA. Three main types of boundaries are used in the published literature on RC buildings. Cradle-to-gate studies include only the production of raw materials up to the point where they leave the factory gate. These are the most common in materials-focused research but do not give a complete picture of the building's environmental impact. Cradle-to-grave studies extend the boundary to include construction, use, maintenance, and end-of-life stages, giving a more complete assessment. Cradle-to-cradle studies go a step further and include the recycling or reuse of materials at the end of the building's life, giving credit for the environmental benefit of returning materials to the production system.

Table 1 summarizes the main LCA stages for RC buildings as defined in the European standard EN 15978, which provides the most widely used framework for building LCA in the literature reviewed.

Table 1. LCA Stages for Reinforced Concrete Buildings: Activities, Typical Energy, and CO_2 Values

LCA Stage	Main Sub-processes	Embodied Energy (GJ/m² floor area)	CO_2 Emissions (kg CO_2-eq/m²)	Key Reference
A1–A3: Material production	Cement, steel, aggregate manufacture; SCM processing	3.5–6.2	280–520	Hossain et al. (2020); Buyle et al. (2013)
A4–A5: Construction	Material transport, on-site mixing, formwork, compaction	0.3–0.8	25–65	Roh et al. (2018); Flower & Sanjayan (2007)
B2–B5: Use & maintenance	Structural repairs, surface coating, component replacement	0.5–2.0 (cumulative 50 yr)	40–160	Marinkovic et al. (2017); Buyle et al. (2013)
B6: Operational energy	Heating, cooling, lighting of occupied building	15–60 (over 50 yr)	500–3000	Chau et al. (2015); Iddon & Firth (2013)
C1–C4: End of life	Demolition, sorting, transport, landfill or recycling	0.1–0.4	10–35	De Schepper et al. (2014); Silvestre et al. (2014)

D: Beyond system boundary	Credits for recycled steel and crushed concrete reuse	−0.5 to −1.2	−40 to −100	Thormark (2006); Passer et al. (2012)

Note: Values are per square meter of gross floor area for a typical mid-rise RC frame building with 50-year reference service life. Operational energy values (Stage B6) dominate the total in most buildings but are highly climate- and design-dependent. End-of-life values (C1–C4) are based on current European practice. Recycling credits (Stage D) are outside the system boundary and shown separately.

2.3 Environmental Indicators Used in RC Building LCA

The most commonly reported indicators in published RC building LCA studies are global warming potential (GWP) measured in kilograms of CO2 equivalent per square meter, and primary energy demand (PED) measured in megajoules or gigajoules per square meter. Some studies also report other impact categories such as acidification potential, eutrophication potential, and depletion of abiotic resources. However, because GWP and PED are consistently reported across almost all studies, they are the main focus of comparison in this review.

An important distinction is made in many studies between embodied energy and operational energy. Embodied energy is the energy used to produce, transport, and assemble the building materials, plus the energy for demolition and disposal. Operational energy is the energy used by the building's occupants during its service life for heating, cooling, lighting, and appliances. In a typical RC building with moderate insulation levels, operational energy over 50 years is often 3 to 10 times larger than embodied energy (Chau et al., 2015). However, as buildings become more energy-efficient due to tighter regulations and better insulation, the relative share of embodied energy is increasing. Iddon and Firth (2013) found that in a well-insulated UK social housing block, embodied energy represented about 28 percent of total life cycle energy, compared to only 12 percent in a poorly insulated equivalent. This shift makes reducing embodied emissions increasingly important.

3. Embodied Energy and Carbon in RC Building Materials

3.1 Contribution of Individual Materials

The largest single contributor to the embodied energy and CO2 of an RC building is ordinary Portland cement (OPC). Hammond and Jones (2008) report embodied energy for OPC of 4.0 to 5.0 megajoules per kilogram and CO2 emissions of 0.74 to 0.95 kilograms per kilogram. In a typical C30 concrete mix with 350 kilograms of cement per cubic meter, cement alone accounts for 70 to 80 percent of the concrete's embodied energy. The mineral aggregates in concrete, despite making up 70 to 75 percent of the volume, have embodied energy of only 0.10 to 0.20 megajoules per kilogram because no high-temperature processing is needed.

Reinforcing steel is the second-largest contributor to embodied energy in RC buildings. Hammond and Jones (2008) report that primary steel (made from iron ore in a blast furnace) has embodied energy of approximately 20 to 29 megajoules per kilogram, while secondary steel made from recycled scrap in an electric arc furnace has embodied energy of only 8.8 to 10.0 megajoules per kilogram. This difference of approximately 65 percent means that the source of steel used in an RC building has a major effect on its total embodied energy. In many countries, including the United Kingdom, United States, and increasingly in China and India, the recycled content of structural steel has been rising, which reduces the overall embodied energy of RC construction.

Table 2 provides a summary of embodied energy and CO2 data for the key materials used in RC buildings, drawn from established published sources.

Table 2. Embodied Energy and CO_2 Emissions of Key Materials Used in RC Buildings

Material	Density (kg/m³)	Embodied Energy (MJ/kg)	CO_2 Emission (kg CO_2-eq/kg)	Source
Ordinary Portland Cement (OPC)	1500	4.0–5.0	0.74–0.95	Hammond & Jones (2008); Habert et al. (2011)
Fly ash (FA)	1100	0.10–0.15	0.004–0.027	Chen et al. (2010); Crossin (2015)
Ground granulated blast-furnace slag (GGBFS)	1200	0.52–0.83	0.05–0.08	Crossin (2015); Habert et al. (2011)
Silica fume (SF)	600	0.14–0.28	0.01–0.02	Van den Heede & De Belie (2012)
Natural crushed aggregate	1600	0.10–0.20	0.006–0.015	Hammond & Jones (2008)
Recycled concrete aggregate (RCA)	1450	0.12–0.22	0.006–0.018	Marinkovic et al. (2017)
Reinforcing steel (bar)	7850	8.8–29.0	0.46–2.82	Hammond & Jones (2008); Roh et al. (2018)
Ready-mixed concrete (C30)	2400	0.75–1.05	0.103–0.159	Flower & Sanjayan (2007); Chen et al. (2010)
Ready-mixed concrete (C40 + 30% FA)	2420	0.58–0.78	0.072–0.110	Chen et al. (2010); Buyle et al. (2013)

Note: All values represent approximate ranges from published studies using different methodologies, system boundaries, and geographic regions. OPC values represent cradle-to-gate embodied energy and CO_2. Steel values depend strongly on the recycled content and production route. Fly ash and GGBFS values represent processing and transport energy only, as production emissions are allocated to the primary industrial process.

3.2 Total Embodied Energy and CO2 for RC Buildings

When the embodied energy of individual materials is combined at the building level, the total depends strongly on the structural system, floor area, number of floors, and design choices. Published studies report a range of 3.5 to 6.2 gigajoules per square meter of floor area for the embodied energy of RC buildings, and 280 to 520 kilograms of CO2 per square meter for embodied carbon (Buyle et al., 2013; Chau et al., 2015; Roh et al., 2018).

Roh et al. (2018) conducted a detailed LCA of a residential building in South Korea with a gross floor area of 7,800 square meters and found that the structure (columns, beams, slabs, and foundation) accounted for 62 percent of the total embodied CO2, while envelope materials (walls, windows, roofing) accounted for 31 percent, and finishing materials the remaining 7 percent. This finding shows that the structural RC frame is by far the most important target for reducing embodied carbon in buildings. Improving the sustainability of the concrete and steel in the structure therefore has a much larger impact than improving the sustainability of secondary building materials.

Chau et al. (2015) studied an 18,500 square meter office building in Hong Kong and found a total embodied energy of 5.3 gigajoules per square meter and embodied CO2 of 430 kilograms per square meter, which was among the higher values in the published literature. The authors attributed this to the high steel intensity of the building's structure (approximately 120 kilograms of steel per square meter of floor area) and the use of 100 percent OPC concrete without any SCM substitution. This study confirms that both the cement and steel components must be addressed to achieve significant reductions in RC building embodied carbon.

3.3 Operational Energy in the Life Cycle Context

While embodied energy from material production dominates in the construction phase, operational energy from heating, cooling, ventilation, lighting, and appliance use during the building's service life is typically the largest single contributor to total life cycle energy. Iddon and Firth (2013) found that for a six-storey UK social housing building with modern but not ultra-low energy standards, operational energy over 60 years was approximately 72 percent of total life cycle energy, while embodied energy was 28 percent. For older buildings or buildings in climates with high heating or cooling demands, the operational share can reach 85 to 90 percent.

This high operational share means that the thermal performance of the building envelope is critical to total life cycle performance. Kim (2011) compared RC office buildings with different levels of insulation in South Korea and found that improving thermal insulation from minimum code requirements to best-practice standards reduced total life cycle CO2 by 22 percent over a 40-year service life. However, this improvement came partly at the cost of additional embodied energy in the insulation materials. The trade-off between additional embodied energy from better insulation and reduced operational energy must be evaluated using LCA to identify the net environmental benefit.

4. Effect of Supplementary Cementitious Materials on LCA Outcomes

4.1 Fly Ash

Fly ash (FA) is a fine powder collected from the flue gases of coal-fired power stations. It consists mainly of glassy spherical particles of silica, alumina, and iron oxide and has pozzolanic properties, meaning it reacts with the calcium hydroxide released during cement hydration to form additional cementitious compounds. Because fly ash is a by-product of power generation, its allocated embodied energy is very low at 0.10 to 0.15 megajoules per kilogram, compared to 4.0 to 5.0 megajoules per kilogram for Portland cement. When fly ash replaces a portion of cement in concrete, the total embodied energy and CO2 of the mix decrease proportionally.

Chen et al. (2010) conducted a detailed LCA of concrete production with varying fly ash contents and found that replacing 30 percent of OPC with fly ash reduced embodied energy from 2.65 to 1.98 gigajoules per cubic meter of concrete, a reduction of 25 percent. CO2 was reduced from 380 to 265 kilograms per cubic meter, a reduction of 30 percent. Flower and Sanjayan (2007) reported similar reductions for Australian concrete and additionally found that the CO2 reduction scaled nearly linearly with FA content up to 50 percent replacement, where the reduction reached 49 percent. At the building level, Roh et al.

(2018) estimated that using 30 percent FA in all structural concrete of a residential building reduced total embodied CO2 by approximately 20 percent compared to the same building designed with 100 percent OPC concrete.

The durability effects of fly ash are also important for LCA. Fly ash reduces the permeability of hardened concrete by refining the pore structure, which improves resistance to chloride ingress and carbonation in certain exposure conditions. Better durability reduces maintenance needs and extends service life, both of which reduce total life cycle environmental impacts. However, some LCA studies note that at very high FA content (above 50 percent), early strength gain is slower, which may require longer curing or higher cement content for high-strength applications, partially offsetting the environmental benefit.

4.2 Ground Granulated Blast-Furnace Slag (GGBFS)

Ground granulated blast-furnace slag (GGBFS) is a by-product of iron manufacturing in a blast furnace. When molten iron slag is rapidly quenched with water, it forms a glassy material with strong latent hydraulic properties that allow it to react with water and calcium hydroxide to form cementitious compounds. GGBFS can replace cement at higher levels than fly ash while still maintaining good strength development, particularly at later ages. Replacement levels of 50 to 70 percent are commonly used in practice.

Crossin (2015) conducted a comprehensive study of GGBFS-blended concrete and found that 50 percent GGBFS replacement reduced CO2 from approximately 380 kilograms per cubic meter to 210 kilograms per cubic meter, a reduction of 45 percent. Habert et al. (2011) confirmed this finding and showed that the GHG reduction scaled with GGBFS content, reaching 54 percent at 70 percent replacement. At the building level, Hossain et al. (2020) studied a multi-storey RC building and found that using 50 percent GGBFS concrete throughout the structure reduced total embodied CO2 by 35 percent compared to OPC concrete, from 395 to 255 kilograms per square meter.

GGBFS also significantly improves the durability of concrete, particularly its resistance to chloride ingress. The chloride diffusion coefficient of 50 percent GGBFS concrete is typically 2 to 4 times lower than OPC concrete, meaning chlorides penetrate much more slowly. This is important for RC buildings in coastal or marine environments, where chloride-induced corrosion of reinforcement is the main durability concern. A longer service life due to better durability amplifies the environmental benefit of GGBFS concrete beyond what the initial production figures suggest.

4.3 Recycled Concrete Aggregate

Recycled concrete aggregate (RCA) is produced by crushing and screening concrete from demolished buildings. It can be used to replace natural coarse aggregate in new concrete. RCA has slightly lower quality than natural aggregate because of the adhered cement mortar remaining on aggregate surfaces, which increases water absorption and reduces density. However, at replacement levels up to 30 percent, the effect on structural concrete performance is small enough to be acceptable within normal design standards.

Marinkovic et al. (2017) studied RC buildings in Serbia and found that using 30 percent RCA in concrete reduced embodied energy by approximately 13 percent and CO2 by approximately 13 percent compared to natural aggregate concrete. The authors noted that the environmental benefit of RCA depends significantly on local transport distances: because demolished buildings in urban areas are close to new construction sites, transport emissions for RCA can be lower than for natural aggregate from quarries outside the city. In the Belgrade case study, RCA transport distances were 30 to 40 percent shorter than natural aggregate transport, which added 3 to 5 percent to the total energy saving.

4.4 Recycled Steel Reinforcement

Steel reinforcement represents a major part of the embodied energy and CO2 of RC buildings. Using steel made from recycled scrap in an electric arc furnace (EAF) rather than primary steel from a blast furnace can reduce embodied energy by approximately 65 to 70 percent and CO2 by similar proportions. Hammond and Jones (2008) report that secondary (EAF) steel has embodied energy of 8.8 megajoules per kilogram compared to 19 to 29 megajoules per kilogram for primary blast furnace steel.

Roh et al. (2018) estimated that if all structural steel reinforcement in a residential building were replaced with 100 percent recycled-content EAF steel, total building embodied CO2 would decrease by approximately 15 to 20 percent, making it the second-largest potential saving after changing the concrete binder composition. In practice, most structural steel reinforcement produced in developed countries already has a recycled content of 60 to 90 percent, but in many developing countries where blast furnace primary steel is still more common, switching to EAF steel offers a substantial and achievable sustainability improvement.

Table 3 provides a comparative summary of published LCA results for RC buildings, showing the range of reported embodied energy and CO2 values, the sustainable strategies applied, and the system boundaries used.

Table 3. Published LCA Results for Reinforced Concrete Buildings: Comparative Summary of Key Studies

Study	Building Type	Floor Area (m^2)	System Boundary	Embodied Energy (GJ/m^2)	CO_2 (kg CO_2-eq/m^2)	SCM / Strategy	Assumed Service Life (yr)
Buyle et al. (2013)	Residential apartment	3,200	Cradle-to-grave	4.8	370	OPC (baseline)	50
Chau et al. (2015)	Office building	18,500	Cradle-to-grave	5.3	430	OPC (baseline)	50
Roh et al. (2018)	Residential (South Korea)	7,800	Cradle-to-gate	3.7	295	30% FA concrete	50
Hossain et al. (2020)	Multi-storey RC frame	12,400	Cradle-to-grave	4.1	310	50% GGBFS concrete	60
Marinkovic et al. (2017)	Residential (Serbia)	5,600	Cradle-to-grave	3.9	325	30% RCA	50
Iddon & Firth (2013)	UK social housing	900	Cradle-to-grave	5.1	405	OPC + insulation	60
Silvestre et al. (2014)	Residential (Portugal)	2,800	Cradle-to-grave	4.6	358	OPC (baseline)	50

Passer et al. (2012)	Office (Austria)	6,200	Cradle-to-cradle	4.3	335	Steel recycling credit	50
Thormark (2006)	Swedish apartment block	4,100	Cradle-to-grave	5.5	380	Timber + RC hybrid	50
Kim (2011)	Office (South Korea)	9,600	Cradle-to-grave	4.9	390	OPC (baseline)	40

Note: GJ/m^2 = gigajoules per square meter of gross floor area. kg CO_2-eq/m^2 = kilograms of CO_2 equivalent per square meter. Values reported are for the material production and construction phases (cradle-to-gate or cradle-to-grave as specified) at the assumed service life. OPC = Ordinary Portland Cement; FA = Fly Ash; GGBFS = Ground Granulated Blast-Furnace Slag; RCA = Recycled Concrete Aggregate.

5. Whole-Life Environmental Performance: Embodied Versus Operational

5.1 Relative Importance of Life Cycle Stages

A central finding of the RC building LCA literature is that while embodied emissions from material production and construction are large and important, they are typically smaller than operational emissions over the full service life of the building. Chau et al. (2015) found that in a Hong Kong office building with a 50-year service life, the operational energy (for cooling, lighting, and equipment) was approximately 82 percent of total life cycle energy, while embodied energy was 18 percent. Iddon and Firth (2013) reported that in UK housing, operational energy over 60 years was 72 percent of the total.

This dominance of operational energy means that the single most effective way to reduce total life cycle impact is to reduce operational energy through better building design and insulation. However, there is a clear diminishing returns effect: as buildings become more energy-efficient, embodied energy becomes a larger and relatively more important share of the total. Thormark (2006) showed that in a very well-insulated Swedish apartment block, embodied energy accounted for approximately 45 percent of total life cycle energy over 50 years, compared to the 15 to 25 percent typical of standard buildings. This means that for nearly zero-energy or passive-house standard RC buildings, decisions about the embodied carbon of structural materials become critically important.

5.2 The Role of Maintenance in the Life Cycle

The use and maintenance phase (Stage B in EN 15978) includes all the repair and maintenance work done to the building's structure during its service life. For RC buildings, this can include crack repair, surface treatment to prevent corrosion, replacement of spalled concrete sections, application of cathodic protection to reinforcement, and in some cases partial structural replacement. All of these activities consume materials and energy, and they contribute to total life cycle emissions.

Buyle et al. (2013) modeled three maintenance scenarios for a Belgian residential building: no maintenance (leading to premature failure), standard maintenance with repainting and minor repairs every 15 years, and enhanced maintenance with corrosion protection treatment every 10 years. Over a 50-year life, the total CO2 difference between no maintenance and enhanced maintenance was 18 to 25 percent of the initial embodied CO2, showing that maintenance decisions have a significant life cycle impact. More durable concrete, which requires less maintenance, therefore has lower total life cycle emissions than indicated by production-phase data alone.

5.3 End-of-Life and Recycling Credits

At the end of a building's service life, the structural materials can be disposed of in several ways. Concrete can be crushed and reused as recycled aggregate (reducing the need for new quarried stone) or simply sent to landfill. Steel reinforcement can be removed and sent to an electric arc furnace for recycling. These end-of-life pathways affect total life cycle impact, but they are outside the main system boundary in many studies.

Passer et al. (2012) conducted a cradle-to-cradle LCA of an Austrian office building and found that recycling credits for structural steel and concrete reduced total embodied CO2 by approximately 15 to 20 percent compared to a cradle-to-grave analysis that ended with landfill. Thormark (2006) found similar results for a Swedish apartment block, reporting that recycling the steel reinforcement alone produced a CO2 credit of approximately 45 kilograms per square meter of floor area, equivalent to about 12 percent of the total embodied CO2. These findings suggest that including end-of-life recycling in RC building LCA is important for making fair comparisons between different structural systems and material choices.

6. Sustainability Strategies for Reducing Environmental Impact of RC Buildings

Table 4 summarizes the key sustainability strategies that have been studied in published journal research, showing the CO2 and energy reduction achievable and the main additional benefits of each approach.

Table 4. Sustainability Strategies for RC Buildings: CO_2 and Energy Reductions from Published Studies

Sustainable Strategy	CO_2 Reduction (%)	Energy Reduction (%)	Additional Benefit	Reference
30% fly ash replacing OPC	25–35	20–30	Improved durability; lower cost	Chen et al. (2010); Flower & Sanjayan (2007)
50% GGBFS replacing OPC	40–54	30–42	Better chloride resistance; longer service life	Crossin (2015); Habert et al. (2011)
30% recycled concrete aggregate (RCA)	10–18	12–16	Reduces quarrying demand	Marinkovic et al. (2017); De Schepper et al. (2014)
Recycled steel reinforcement	30–55	40–60	Reduces primary steel demand	Hammond & Jones (2008); Roh et al. (2018)
Thermal insulation (passive design)	15–40 (operational)	20–50 (operational)	Reduces heating/cooling energy use	Iddon & Firth (2013); Chau et al. (2015)
Extended service life (50→100 years)	30–40 per year of service	30–40 per year of service	Amortises embodied impact over longer period	Buyle et al. (2013); Hossain et al. (2020)

Blended cement (FA + GGBFS together)	45–60	35–50	Synergistic durability and strength gain	Van den Heede & De Belie (2012); Kim (2011)
High-strength concrete (HSC) reducing cross-section	8–15	5–12	Smaller structural members; less material	Passer et al. (2012); Buyle et al. (2013)
Modular prefabricated RC elements	10–20	8–18	Reduced waste and faster construction	Roh et al. (2018); Silvestre et al. (2014)

Note: Reduction percentages are relative to equivalent OPC concrete or standard design baseline as specified in the referenced studies. Operational energy reductions apply only to thermal insulation and passive design strategies. All other reductions refer to embodied energy and CO_2 in the material production phase.

The data in Table 4 shows that blended cement systems using both FA and GGBFS together offer the largest single-material CO2 reductions of 45 to 60 percent compared to OPC baseline, while also providing synergistic improvements in durability through complementary reactions that improve pore structure and reduce permeability. Van den Heede and De Belie (2012) showed that FA and GGBFS act in different temperature and humidity conditions, meaning a blend of the two provides more reliable and consistent performance across different curing and service conditions than either material alone.

Extended service life has an effect that is often larger than any material substitution strategy when expressed per year of useful service. Buyle et al. (2013) showed that doubling the service life from 50 to 100 years effectively halves the environmental cost per year of function, which is equivalent to a 50 percent reduction in annualized impact. However, achieving a 100-year service life requires design decisions about cover depth, concrete mix, and corrosion protection that must be made at the construction stage and cannot easily be retrofitted later.

Using high-strength concrete (HSC) allows smaller structural cross-sections for the same load-bearing capacity, which reduces the total volume of concrete and therefore the total embodied energy and CO2. Passer et al. (2012) found that using C50 concrete instead of C30 for columns and slabs in an Austrian office building reduced structural concrete volume by approximately 18 percent, leading to a 6 to 10 percent reduction in total structural embodied CO2 despite the higher cement content per cubic meter of HSC.

7. Durability of RC Buildings and Its Effect on LCA

7.1 Why Durability Matters for Life Cycle Sustainability

The durability of an RC building determines how long it performs its structural function without needing major repair or replacement. A more durable building not only reduces maintenance costs but also reduces the total environmental impact per year of service, because the large initial investment in materials and construction is spread over a longer useful life. When two buildings are compared on an embodied energy per square meter basis assuming the same 50-year life, but one actually lasts 80 years and the other needs significant structural repair at year 35, the comparison is not fair. The building that lasts longer is better from a life cycle environmental perspective, but this advantage is invisible in a standard 50-year fixed-life LCA.

The main processes that reduce the durability of RC structures are: carbonation of concrete leading to corrosion of steel reinforcement when the carbonation front reaches the steel; chloride ingress from marine environments or de-icing salts, also leading to corrosion; sulfate attack on concrete in soils or groundwater containing sulfate; and freeze-thaw deterioration in cold climates. Each of these processes proceeds at a rate that depends on the concrete mix, the cover depth over the reinforcement, and the environmental exposure conditions.

7.2 Effect of SCMs on Concrete Durability

SCMs generally improve the durability of concrete by refining the pore structure and reducing permeability. GGBFS at 50 to 70 percent content reduces chloride diffusion coefficients to 1.8 to 4.5 times 10 to the power of negative 12 square meters per second, compared to 8.5 to 12.0 times 10 to the power of negative 12 for OPC concrete. This means chlorides penetrate much more slowly in GGBFS concrete, extending the time to corrosion initiation by a factor of 2 to 4 depending on cover depth and exposure severity (Lothenbach et al., 2011).

Silica fume at 5 to 10 percent content provides the largest reduction in permeability of all SCMs. Van den Heede and De Belie (2012) reviewed experimental data and found that silica fume concrete typically has a chloride diffusion coefficient 4 to 6 times lower than OPC concrete at similar water-to-binder ratios, resulting in predicted service lives of 80 to 110 years in moderate chloride exposure compared to 50 to 65 years for OPC concrete.

Fly ash concrete has intermediate durability performance. At 30 percent replacement, fly ash concrete shows modest improvements in chloride resistance and carbonation resistance compared to OPC concrete. At 50 percent replacement, chloride resistance is significantly improved but carbonation depth increases slightly because the pozzolanic reaction consumes calcium hydroxide, reducing the concrete's alkalinity reserve (Atis, 2003). This means high-FA concretes may be more suitable for environments where chloride attack is the main threat (coastal areas) and less suitable for urban environments where air CO2 levels drive carbonation.

7.3 Durability-Adjusted LCA

Several published studies have attempted to include durability in their LCA by using variable service lives for different mix designs rather than a fixed 50-year life. Hossain et al. (2020) compared OPC and 50 percent GGBFS concrete for a multi-storey RC building assuming 50-year and 80-year service lives respectively, based on chloride diffusion modelling for the local coastal exposure conditions. They found that the total life cycle CO2 per year of service was 37 percent lower for GGBFS concrete than for OPC concrete, significantly larger than the 35 percent reduction seen in the standard production-phase comparison. This confirms that including durability in LCA increases the measured environmental advantage of durable SCM concretes.

The challenge of implementing durability-adjusted LCA is that it requires reliable service life prediction models and data on the durability of the specific concrete mixes being compared. The fib Model Code 2010 provides probabilistic service life models for carbonation-induced and chloride-induced corrosion that can be applied to this purpose. These models use concrete composition data (chloride diffusion coefficient, carbonation coefficient) and structural data (cover depth) to predict time to corrosion initiation as a function of environmental exposure. Coupling these models with LCA has been demonstrated in several studies but is not yet standard practice.

8. Research Gaps

The review of published literature has identified several important research gaps in the LCA of RC buildings. These are summarized in Table 5 and discussed in detail below.

Table 5. Research Gaps Identified in Published LCA Studies on RC Buildings

Research Gap	Description	Consequence for LCA	Suggested Future Direction
Durability not linked to service life	Fixed 50-year life used regardless of material quality	Underestimates benefit of durable SCM concretes	Couple fib Model Code durability models with LCA framework
Operational vs embodied energy balance	Most RC building LCAs focus only on embodied phase	Total life cycle impact is incomplete without operational phase	Use whole-building energy simulation alongside LCA
Lack of developing-country LCA data	Most databases are European or North American	Results not applicable to India, Southeast Asia, Africa	Develop region-specific material inventory databases
End-of-life recycling rarely included	Recycling credits for steel and concrete rarely counted	Understates circular economy benefit	Apply cradle-to-cradle LCA and quantify recycling credits
Carbonation CO_2 uptake ignored	Concrete absorbs CO_2 during service and demolition	Net CO_2 overestimated by approximately 5–15%	Include natural carbonation models in LCA inventory
Multi-storey and high-rise LCA data limited	Most studies use low-rise or medium-rise buildings	Cannot generalise results to tall RC buildings	Conduct dedicated LCA for 10+ storey RC frame buildings

Note: fib = International Federation for Structural Concrete. LCA = Life Cycle Assessment. SCM = Supplementary Cementitious Material.

The most significant gap is the near-universal use of a fixed 50-year service life in published LCA studies, regardless of the concrete mix or exposure conditions. This practice systematically underestimates the environmental benefit of more durable concrete mixes. Only a small number of published studies have used variable service lives based on quantitative durability modelling. Developing a standard protocol for durability-adjusted LCA of RC buildings would be a major step forward for the field.

A second important gap is the poor integration of operational and embodied energy in building LCA research. Many material-focused studies (such as those comparing concrete mix options) use only embodied energy as the indicator and ignore operational energy entirely. Conversely, many building energy performance studies focus on operational energy and ignore embodied energy. A whole-life perspective that combines both is essential for finding the true best design option, but such integrated studies are still relatively rare.

A third gap is the very limited availability of published LCA data for RC buildings in developing countries. The overwhelming majority of published studies use data from Europe, North America, Japan, South Korea, and Australia. In countries like India, Indonesia, Nigeria, Brazil, and Egypt, where RC building construction is growing extremely rapidly, local energy mixes, construction practices, cement types, and available SCMs are very different from those in the published literature. Applying European or Australian LCA results to construction decisions in these countries could lead to seriously misleading conclusions.

A fourth gap relates to the end-of-life phase. Most RC building LCA studies either stop at end of life (cradle-to-grave) without giving credit for material recycling, or they assume optimistic future recycling scenarios without robust data. Given that concrete is the world's most widely produced construction material and will generate enormous volumes of demolition waste as today's buildings reach end of life over the next 50 to 100 years, quantifying the environmental benefit of concrete recycling strategies is an important research priority.

9. Future Research Directions

9.1 Durability-Integrated LCA Models

The highest-priority future research direction is the development of validated, standardized methods for integrating concrete durability into building LCA. This requires three linked advances: robust service life prediction models validated by long-term field data; a standardized protocol for translating service life differences between mix designs into equivalent life cycle environmental impacts; and practical software tools that allow building designers to evaluate the combined effect of concrete mix choice on both initial embodied energy and service life. The fib Model Code 2010 durability models provide a strong scientific basis for this work.

9.2 Regional LCA Databases for Developing Countries

There is an urgent need for region-specific LCA databases and studies covering countries in South Asia, Southeast Asia, Africa, and Latin America. India in particular is a critical gap: India is the world's second-largest cement producer with approximately 330 million tonnes per year (IEA, 2022), and its RC building construction sector is growing at rates of 6 to 8 percent per year. The embodied energy and CO2 of concrete produced in India using local cement types, locally available SCMs such as fly ash from Indian coal-fired power plants, and local steel with its specific recycled content profile, cannot be assumed to be the same as in European or Australian studies.

9.3 Whole-Building Integrated LCA and Energy Modelling

Future studies should combine building energy simulation (using tools such as EnergyPlus or IDA ICE) with material LCA to evaluate the full life cycle performance of RC building designs. This approach allows simultaneous optimization of both embodied and operational energy, identifying the combination of structural system, concrete mix, and envelope design that gives the lowest total life cycle impact. Such integrated studies are computationally demanding but are increasingly feasible as computing power and software capabilities improve.

9.4 Machine Learning and Data-Driven Approaches

Machine learning methods have shown strong potential for predicting material properties such as compressive strength, chloride diffusion coefficient, and embodied energy from concrete mix design parameters. Extending these methods to whole-building LCA prediction, where a building design is described by a set of parameters and the model predicts total life cycle energy and emissions, could make LCA much faster and more accessible to practicing engineers. Developing large training datasets from existing published LCA studies and building databases would be the critical first step.

9.5 Circular Economy in RC Building Construction

The potential of circular economy approaches for RC buildings, including designing buildings for disassembly, using modular precast concrete systems that can be reused rather than demolished, and maximizing the recycled content of both concrete and steel, deserves much more attention in the LCA literature. De Schepper et al. (2014) showed that completely recyclable concrete, where the concrete is designed so that both the aggregate and the cementitious material can be recovered and reused at end of life, could reduce total life cycle CO2 by 30 to 40 percent compared to conventional concrete with landfill disposal. Scaling this concept to full RC buildings is a challenging but potentially high-impact research direction.

10. Conclusions

This review has examined the published journal literature on the life cycle assessment of reinforced concrete buildings for sustainable construction. The following main conclusions are drawn:

1. Reinforced concrete buildings have significant environmental impacts across their life cycle. Embodied energy from material production and construction typically ranges from 3.5 to 6.2 gigajoules per square meter, and embodied CO2 ranges from 280 to 520 kilograms per square meter. Cement production and structural steel are the two dominant contributors to these impacts.
2. Supplementary cementitious materials (SCMs) are the most effective means of reducing the embodied carbon of RC buildings. Replacing 30 percent of OPC with fly ash reduces CO2 by 25 to 35 percent. Replacing 50 percent of OPC with GGBFS reduces CO2 by 40 to 54 percent. Blended FA and GGBFS systems can reduce CO2 by 45 to 60 percent while also improving concrete durability.
3. Operational energy dominates total life cycle energy in most RC buildings, representing 70 to 85 percent of the total over a 50-year service life in buildings with standard insulation levels. However, as building energy performance improves under tightening regulations, embodied energy becomes a progressively larger and more important share of the total impact.
4. Concrete durability has a direct and significant effect on life cycle environmental performance. A more durable concrete that extends building service life from 50 to 100 years reduces annualized embodied impact by approximately 40 to 50 percent. Despite this, the majority of published LCA studies use a fixed 50-year service life and do not account for durability differences between mix designs.
5. End-of-life recycling credits for structural steel and concrete can reduce total embodied CO2 by 12 to 20 percent but are routinely excluded from published LCA studies, leading to overestimation of the net environmental impact of RC construction.
6. Six key research gaps were identified: the absence of durability-based service life modeling in LCA; poor integration of embodied and operational energy; lack of published data from developing countries; limited cradle-to-cradle end-of-life analysis; exclusion of carbonation CO2 uptake; and insufficient LCA data for tall RC buildings.

Future research should prioritize durability-integrated LCA frameworks, development of regional databases for rapidly growing economies such as India, whole-building integrated LCA and energy simulation, and the application of machine learning to make LCA more accessible for practicing engineers.

Achieving truly sustainable RC construction requires designing for both lower initial emissions and longer, more durable service lives.

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