



Evaluating Performance, Durability and Environmental Benefits of Low-carbon Concrete: A Comprehensive Review

Srinivasa Reddy Vempada^{1*}, Shrihari Saduwale², Kandoori Roja² and Shoeb Mohammed²

¹Department of Civil Engineering, KG Reddy College of Engineering and Technology, TG, India

²Department of Civil Engineering, Vidya Jyothi Institute of Technology, TG, India

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*srinivasareddy.v@kgr.ac.in



ABSTRACT

Low-carbon concrete offers a critical solution to cut CO₂ emissions from traditional concrete. This review highlights its composition, benefits, and performance, with a focus on supplementary cementitious materials such as fly ash and slag, which partially replace Portland cement to reduce embodied carbon. Alternative binders, such as geopolymers and magnesium-based cements, further reduce emissions and improve durability. Carbon capture and utilization technologies also help reduce emissions by binding CO₂ during curing. Studies show that low-carbon concrete can achieve mechanical properties comparable to those of conventional concrete, with potential carbon reductions of up to 22%. Optimized mix design, continued research, and strong policy support are essential for its widespread adoption.

Keywords: Low-carbon concrete; Supplementary cementitious materials; Carbon capture and utilization; Sustainable construction; Life-cycle assessment.

1. INTRODUCTION

Low-carbon concrete is a sustainable alternative to traditional concrete, designed to reduce greenhouse gas emissions associated with cement production, a major contributor to global CO₂ emissions. By reducing the amount of cement or replacing it with supplementary cementitious materials (SCMs), low-carbon concrete can significantly lower the environmental impact of construction while maintaining performance standards. Low-carbon concrete is designed to substantially reduce greenhouse gas emissions associated with traditional cement production by using innovative materials and methods (Hakkinen and Belloni, 2011). Key approaches include the use of supplementary cementitious materials such as fly ash, slag, silica fume, and calcined clay, which can partially replace Portland cement, enhancing durability while reducing the carbon footprint. Carbon capture and utilization (CCU) is another method, where concrete absorbs CO₂ during curing, permanently binding it in the material to lower emissions and improve strength. Carbon capture, utilization, and storage technology is an exciting innovation in the concrete industry (Kou and Poon, 2009). Carbon capture theoretically makes it possible to capture up to 100% of the carbon emissions from cement manufacturing. These captured emissions can be stored safely underground, injected back into concrete to strengthen it, or used to make other products like synthetic aggregates or fuels. Alternative binders, such as

geopolymers and magnesium-based cements, provide low-carbon or even carbon-negative solutions by leveraging industrial byproducts like fly ash and slag. Incorporating recycled aggregates, such as crushed concrete from demolition, and using plastic fibre reinforcement, including plastic fibre aggregate bricks, lowers the demand for new materials while enabling the reuse of high-volume plastic waste (Yazan, 2023). A shift toward performance-based specifications allows for alternative, lower-carbon materials to meet strength and durability standards without compromising structural integrity. Lastly, optimizing the mix design, particularly by reducing cement content and adjusting the water-to-cement ratio, further reduces the environmental impact of concrete, aligning with sustainability goals for construction. By implementing low-carbon concrete in construction, builders and engineers can contribute significantly toward sustainability goals, particularly in net-zero initiatives. Given the focus on sustainable building materials and high-volume plastic reuse, integrating low-carbon concrete into construction projects could complement efforts to make building practices more eco-friendly and resource-efficient.

Concrete is the backbone of modern infrastructure, yet its dependence on Portland cement makes it a major contributor to global CO₂ emissions. With the construction sector under increasing pressure to decarbonize, there is an urgent need to explore low-carbon alternatives that can balance sustainability with

performance. Low-carbon concrete, incorporating SCMs (such as fly ash and slag), alternative binders (including geopolymers and magnesium-based cements), and carbon capture and utilization technologies, offers a promising solution. While many studies have addressed individual materials and techniques, a comprehensive review that integrates their environmental, mechanical, and durability aspects is lacking. This study addresses the gap by integrating existing knowledge, quantifying potential emission reductions, and highlighting challenges to large-scale adoption. The review provides valuable insights for researchers, engineers, and policymakers aiming to advance sustainable construction practices in line with international climate goals.

2. LOW-EMBODIED-CARBON CONSTITUENTS

Low-embodied-carbon constituents in concrete are materials that reduce the carbon emissions associated with the production, transportation, and use of concrete components (Amran *et al.* 2015).

Traditional concrete production is highly energy-intensive and a significant source of CO₂ emissions, with high embodied carbon primarily due to its cement content. To counter this, low-carbon alternatives and replacements have emerged, offering sustainable solutions that minimize environmental

impact while maintaining concrete's durability and structural performance.

Table 1 quantifies typical reductions in embodied carbon for each low-carbon constituent and technique in concrete production. Fig. 1 depicts the embodied carbon reduction percentages for various carbon constituents and techniques. The techniques presented for reducing embodied carbon in concrete highlight various effective strategies for achieving sustainability in construction. Fly ash, a byproduct of coal combustion, can replace a portion of cement, reducing embodied carbon by 15–30% while enhancing durability and workability. Similarly, Ground Granulated Blast-Furnace Slag (GGBFS), a byproduct of steel manufacturing, can lower clinker content and achieve a reduction of 30–50%, improving both strength and sulfate resistance. Silica fume, derived from silicon alloy production, provides a 10–20% reduction while increasing strength and reducing permeability. The innovative LC3 (Limestone-calcined clay cement) combines limestone and calcined clay, resulting in a 20–40% reduction in carbon emissions while enhancing early strength and minimizing shrinkage. Geopolymer cement, produced from fly ash and slag, can replace traditional cement entirely, offering a remarkable reduction of 70–90% with high durability and low thermal conductivity. Magnesium-based cements can potentially achieve a 100% reduction through CO₂ absorption during curing, making them carbon-negative.

Table 1. Embodied carbon for low-carbon constituents and techniques in concrete production

Low-embodied Carbon Constituent/Technique	Description	Embodied Carbon Reduction	Additional Benefits
Fly Ash	Byproduct of coal combustion, replaces a part of cement	15–30%	Enhances durability and workability
GGBFS	Steel manufacturing byproduct reduces clinker content in cement	30–50%	Improves strength and sulfate resistance
Silica Fume	Byproduct of silicon alloy production, used in small quantities	10–20%	Increases strength and reduces permeability
LC3	Combines limestone and calcined clay as a partial cement replacement	20–40%	Increases early strength and reduces shrinkage
Geopolymer Cement	Made from fly ash, slag, and aluminosilicates, replacing traditional cement completely	70–90%	High durability, low thermal conductivity
Magnesium-based Cement	Absorbs CO ₂ during curing; can be carbon-neutral or carbon-negative	100% (potentially carbon-negative)	High CO ₂ sequestration potential
Recycled Concrete Aggregates (RCA)	Reuses crushed concrete from demolished structures to replace virgin aggregate	10–20%	Reduces landfill waste, minimizes extraction impacts
Carbon Curing (Carbon Sequestration)	Injects CO ₂ into concrete during curing, binding it permanently.	Up to 10%	Strengthens concrete, especially in early stages
Recycled Plastic Fiber Reinforcement	Incorporates recycled plastic fibres to replace some steel reinforcement	10–15%	Diverts plastic waste from landfills
Optimized Mix Design	Reduces cement content and adjusts proportions to achieve the target strength with less embodied carbon	10–25%	Enhances efficiency and can reduce material costs

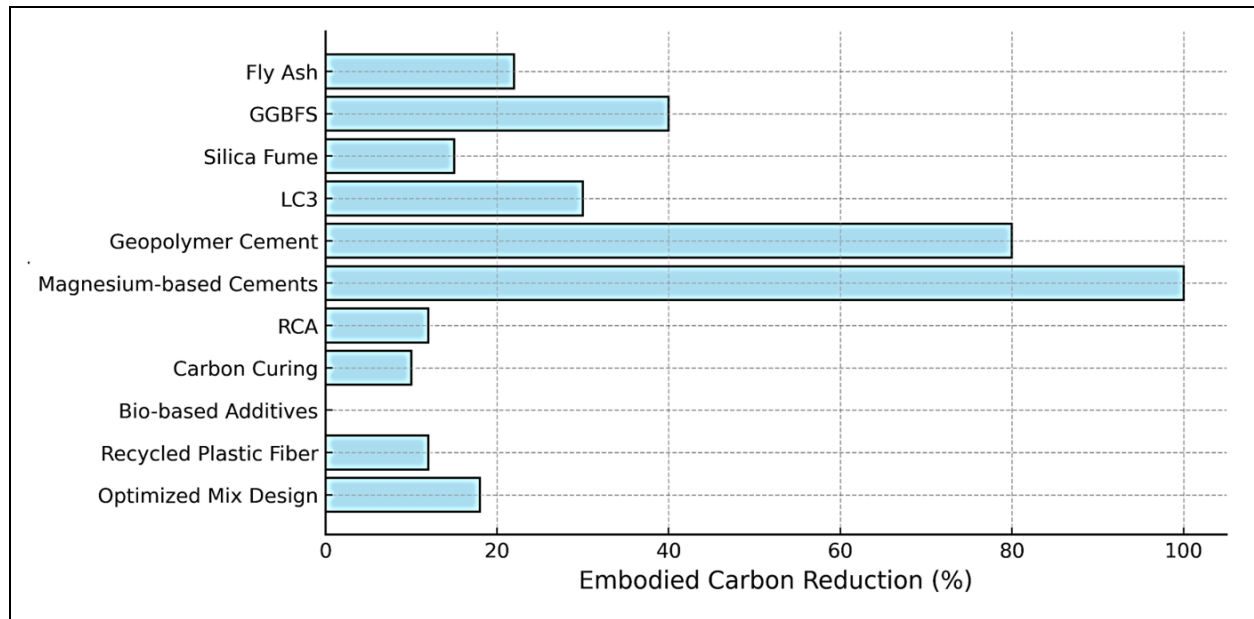


Fig. 1: Histogram depicting the embodied carbon reduction percentages for various low-embodied-carbon constituents and techniques

Utilizing RCA can achieve a 10–20% reduction while minimizing landfill waste. The carbon curing method injects CO₂ into concrete during curing. This leads to about a 10% reduction of carbon emissions and enhancement of early strength. Additionally, bio-based additives can sequester CO₂, resulting in variable reductions in embodied carbon, while recycled plastic fiber reinforcement diminishes waste and achieves a 10–15% reduction. Moreover, an optimized mix design reduces cement content and achieves a 10–25% reduction. This enhances material efficiency apart from potentially lowering costs.

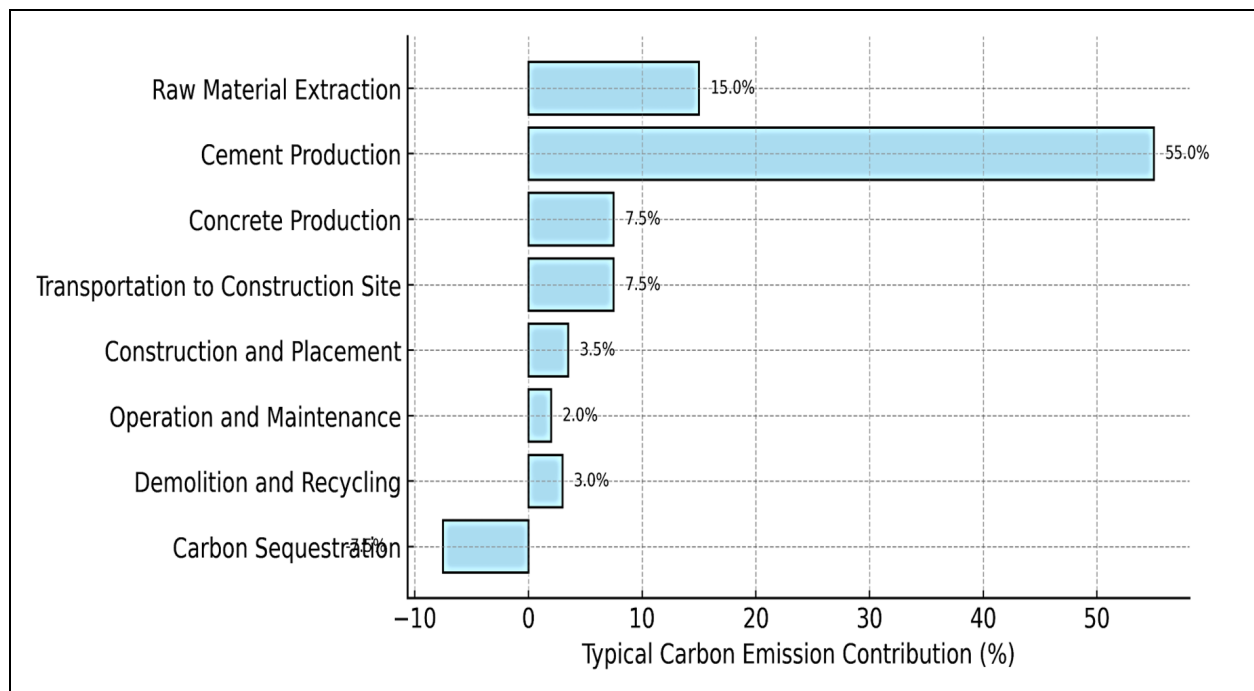
3. CARBON EMISSION LIFE CYCLE OF CONCRETE

The carbon emission life cycle of concrete construction can be broken down into stages, each contributing to the overall carbon footprint. Table 2 outlines the primary life cycle stages of concrete, their description, and typical carbon emission contributions. The life cycle of concrete involves several stages, each contributing to its overall carbon emissions. Raw material extraction, which includes the mining and processing of limestone, clay, and aggregates, typically contributes 10–20% of the total emissions, primarily from mining, crushing, and transportation. Cement production is the most significant phase, accounting for 50–60% of emissions due to fuel combustion and the release of CO₂ during the calcination of limestone. The

concrete production phase adds another 5–10% through energy use for mixing and transportation to the construction site. Transportation of materials to the construction site further contributes 5–10% to fuel emissions associated with various transportation modes. On-site construction activities, including formwork and curing, contribute 2–5% to emissions through the use of equipment and energy. The operation and maintenance phase, although minimal for low-maintenance concrete structures, accounts for 1–3% of emissions due to occasional maintenance and repairs. At the end of its life cycle, the demolition and recycling phase generates 1–5% of emissions from the machinery used and the transportation of waste. However, concrete has a unique characteristic of carbon sequestration, where natural carbonation can lead to a reduction in emissions by 5–10% as CO₂ is absorbed by the concrete over time. Carbon sequestration contributes a negative carbon value, as concrete absorbs CO₂ through natural carbonation over its lifespan, which offsets a small portion of emissions. Cement production remains the largest contributor to total emissions in concrete construction due to the high energy demands and CO₂ emissions from calcination. Transportation emissions can vary significantly depending on distance and transportation modes, with locally sourced materials minimizing this contribution. The operational and maintenance phase typically has a low carbon impact, as concrete structures require low maintenance. Fig. 2 shows the typical carbon emission contributions by stages of the concrete life cycle.

Table 2. Carbon emission life cycle of concrete

Life-cycle Stage	Description	Typical Carbon Emission Contribution	Emission Sources
Raw Material Extraction	Extraction and processing of raw materials, including limestone, clay, and aggregates	10–20%	Mining, crushing, and transportation of raw materials
Cement Production	Manufacturing of cement, primarily clinker production through limestone calcination	50–60%	Fuel combustion, CO ₂ from calcination in kilns, and electricity
Concrete Production	Mixing of cement, aggregates, water, and additives to produce concrete	5–10%	Energy use for mixing, transport to the site, and admixtures
Transportation to Construction Site	Transport of raw materials, cement, and concrete to the construction site	5–10%	Fuel emissions from trucks and other transportation modes
Construction and Placement	On-site processes, including formwork, concrete pouring, vibrating, and curing	2–5%	Equipment use, curing processes, and energy for on-site work
Operation and Maintenance	Lifespan of the structure, including maintenance activities to prolong durability (minimal for low-maintenance concrete)	1–3%	Occasional maintenance (if needed) and energy use for repairs
Demolition and Recycling	Demolition of the structure at the end of its life cycle, with potential recycling of concrete	1–5%	Demolition machinery, recycling, and transportation of waste

**Fig. 2: Histogram showing the typical carbon emission contributions by life cycle stage for concrete**

4. MATERIALS AND TECHNOLOGIES FOR LOW-CARBON CONCRETE

Table 3 summarizes the studies conducted on low-carbon concrete, focusing on the replacement of cement with materials such as geopolymers, GGBFS, and other admixtures. Several researchers have explored the use of GGBFS and other supplementary materials as sustainable alternatives in concrete production. Hossain (2023), investigated geopolymer concrete with a 100% replacement of cement using GGBFS, highlighting its mechanical properties and sustainability potential. examined concrete with 20%, 30%, and 40% GGBFS replacement, and found that certain levels

enhanced the mechanical properties and durability. In another study, assessed the effects of substituting up to 15% of GGBFS with circulating fluidized bed combustion bottom ash and metakaolin, discovering improvements in the split-tensile strength of self-compacting concrete. Additionally, analyzed the partial replacement of cement with varying percentages of GGBFS and fly ash, demonstrating that the resulting mixes exhibited compressive and tensile strengths comparable to ordinary Portland cement Shao *et al.* (2000). These findings collectively emphasize the potential of GGBFS and its combinations in enhancing concrete performance and sustainability. The above studies illustrate the potential of using alternative

materials to replace traditional cement in concrete, thereby reducing carbon emissions and, in some cases, enhancing performance.

A range of innovative materials and methods now offer substantial carbon reductions in concrete production. Fly ash can replace part of the cement and typically cuts carbon emissions while improving durability and workability in concrete. GGBS provides a similar function, achieving carbon reduction and enhancing sulfate resistance. Silica fume yields a reduction in emissions, strengthens the concrete, and lowers its permeability. LC3 offers carbon reduction while improving early strength. Geopolymer cement can reduce emissions and provide a durable, heat-resistant alternative. Magnesium-based cements, which absorb CO₂ as they cure, can be carbon-neutral or even carbon-negative, depending on the application. Other promising

methods include carbon curing, which injects CO₂ during the curing process to improve early strength and reduce permeability, achieving carbon reduction. Bio-based additives, including organic fibers and microorganisms, enhance CO₂ absorption. Recycled plastic fibers, often from PET, can replace steel reinforcement, reducing emissions by 10–15% while diverting plastic from landfills. Optimized mix designs, which use reduced cement content, lower emissions, and improve resource efficiency. Self-healing concrete, containing bacteria or other agents to seal cracks, can reduce maintenance needs and lifecycle emissions by 5–10%. These technologies collectively enable greener concrete by cutting emissions, reducing reliance on new resources, and enhancing durability, offering a more sustainable solution for construction. Fig. 3 illustrates the typical carbon reduction percentages of various sustainable concrete technologies.

Table 3. Materials and technologies for low-carbon concrete

Material/Technology	Description	Additional Benefits
Fly Ash	A byproduct of coal combustion, which replaces a portion of cement	Enhances durability and workability, and reduces the heat of hydration
Ground Granulated Blast-Furnace Slag	Steel industry byproduct that partially replaces cement	Improves sulfate resistance and durability
Silica Fume	Byproduct of silicon alloy production, used in small quantities	Increases strength, reduces permeability, and enhances durability
Limestone-calcined Clay Cement	Partially replaces cement with limestone and calcined clay	Reduces shrinkage, enhances early strength, and improves sustainability
Geopolymer Cement	Cement alternative made from aluminosilicate materials like fly ash and slag	High durability, reduced heat of hydration, and low thermal conductivity
Magnesium-based Cements	Alternative cement that absorbs CO ₂ during curing, potentially carbon-neutral	Can sequester CO ₂ , potentially carbon-negative in some applications
Recycled Concrete Aggregates	Reuses crushed concrete from demolition to replace virgin aggregates	Reduces landfill waste and lowers demand for virgin materials
Recycled Plastic Fiber Reinforcement	Uses fibers from recycled plastics (e.g., PET) to reinforce concrete, reducing steel use	Diverts plastic waste from landfills; a lightweight alternative to steel
Self-healing Concrete	Contains bacteria or other agents that repair cracks over time, reducing maintenance needs	Reduces lifecycle emissions, increases concrete longevity

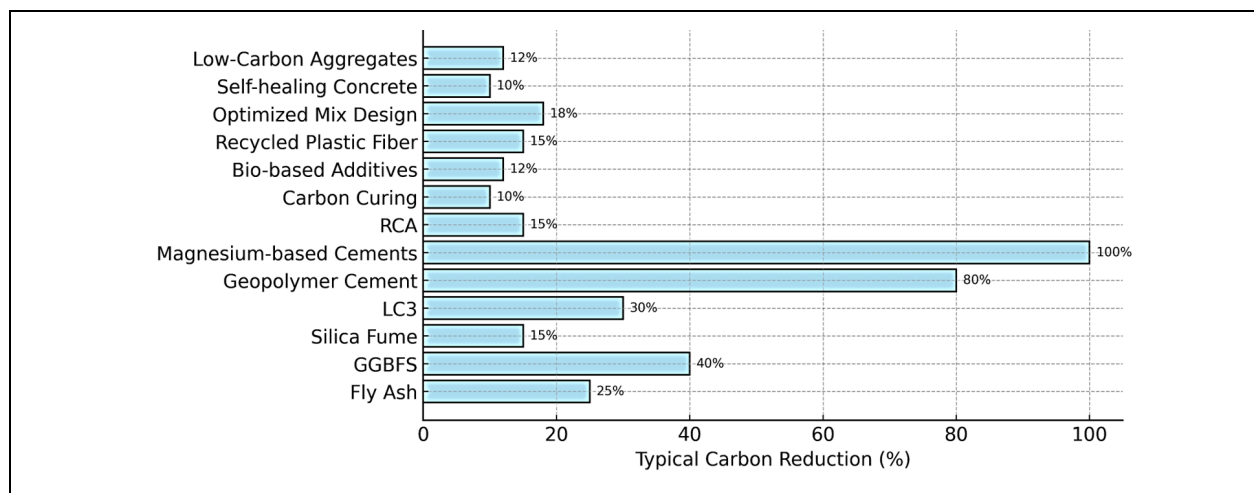


Fig. 3: Carbon reduction percentages of various sustainable concrete technologies

5. ALTERNATIVE MATERIALS AS CLINKER REPLACEMENT

Table 4 lists alternative materials that can replace clinker in cement production, with descriptions, typical clinker replacement levels, carbon reduction potential, and additional benefits. Clinker replacement levels depend on the material's reactivity and the required strength specifications. Carbon reduction potential reflects the reduction in emissions relative to clinker, which has a high carbon footprint. Natural pozzolans,

such as volcanic ash, can replace 15–30% of clinker and achieve a 10–25% reduction in emissions, while also enhancing durability and resistance to chemical attack. Rice husk ash, a byproduct of rice milling, replaces clinker at 10–20% with a 10–15% reduction in emissions, contributing to waste repurposing and durability improvement (Srinivasan and Sathiya, 2010). Metakaolin, a highly reactive calcined clay, can replace 10–20% of clinker, providing a 15–25% reduction in emissions and enhancing concrete strength and durability.

Table 4. Alternative materials as clinker replacement

Alternative Material	Description	Additional Benefits
Fly Ash	Byproduct of coal combustion, used as a pozzolan to partially replace clinker.	Increases workability, reduces heat of hydration, and improves durability.
GGBFS	Byproduct of steel manufacturing, used as a clinker replacement.	Enhances sulfate resistance, reduces permeability.
Silica Fume	Byproduct from silicon alloy production, used in small amounts to increase strength and durability.	Increases concrete strength, reduces permeability.
LC3	Calcined clay combined with limestone, creating LC3	Enhances early strength, reduces shrinkage, sustainable alternative.
Natural Pozzolans	Naturally occurring volcanic ash or diatomaceous earth, reactive with cement.	Improves durability, reduces chemical attack susceptibility.
Rice Husk Ash	A byproduct from rice milling; it can replace clinker as a pozzolanic material	Reduces agricultural waste, increases durability.
Metakaolin	Calcined kaolin clay acts as a highly reactive pozzolan in cement mixes.	Increases strength, reduces permeability, and improves durability.
Recycled Concrete Fines	Pulverized concrete waste that partially replaces clinker in new mixes.	Reduces landfill waste, supports the circular economy.

Limestone filler, which dilutes cement content, allows a 5–15% clinker replacement, achieving a similar carbon reduction and improving workability. Recycled concrete fines, sourced from pulverized concrete waste, can replace 10–20% of clinker, reducing both landfill waste and carbon emissions by 10–15%, thus supporting the circular economy (Silva *et al.* 2014). Finally, magnesium silicate can substitute 20–50% of clinker, with the potential for carbon capture during curing, offering up to a 100% carbon reduction, potentially achieving carbon-neutral or carbon-negative applications and enhancing concrete durability. These alternative materials collectively support lower-carbon concrete production through clinker substitution, reduced waste, and enhanced material properties. Fig. 4 displays the

clinker replacement level and carbon reduction potential for each alternative material.

6. CEMENT REPLACEMENT LEVEL AND CARBON REDUCTION POTENTIAL

Table 5 quantifies the impact of various SCMs in reducing cement content in concrete mixtures. It includes typical replacement levels and carbon reduction potential of each SCM. These SCMs collectively support a more sustainable approach to concrete production by reducing reliance on cement, lowering emissions, and improving material properties. Fig. 5 displays the cement replacement level and carbon reduction potential for each SCM.

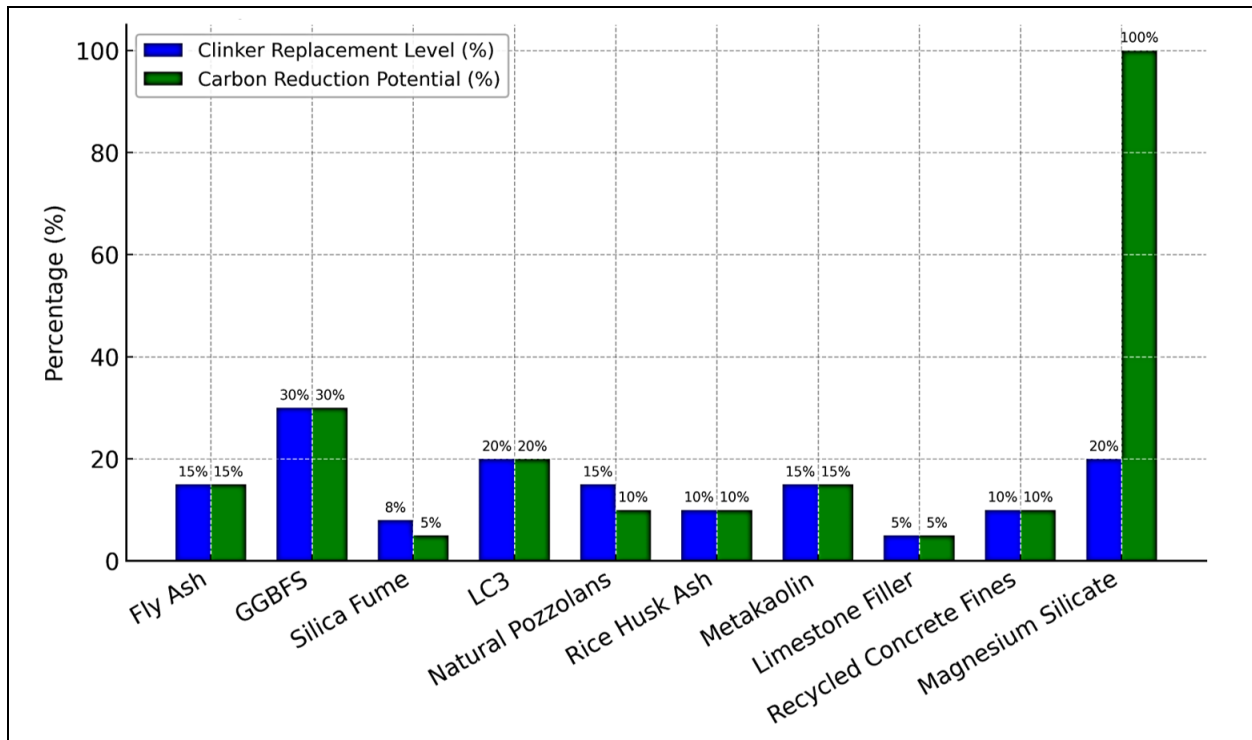


Fig. 4: Clinker replacement level and carbon reduction potential for alternative materials

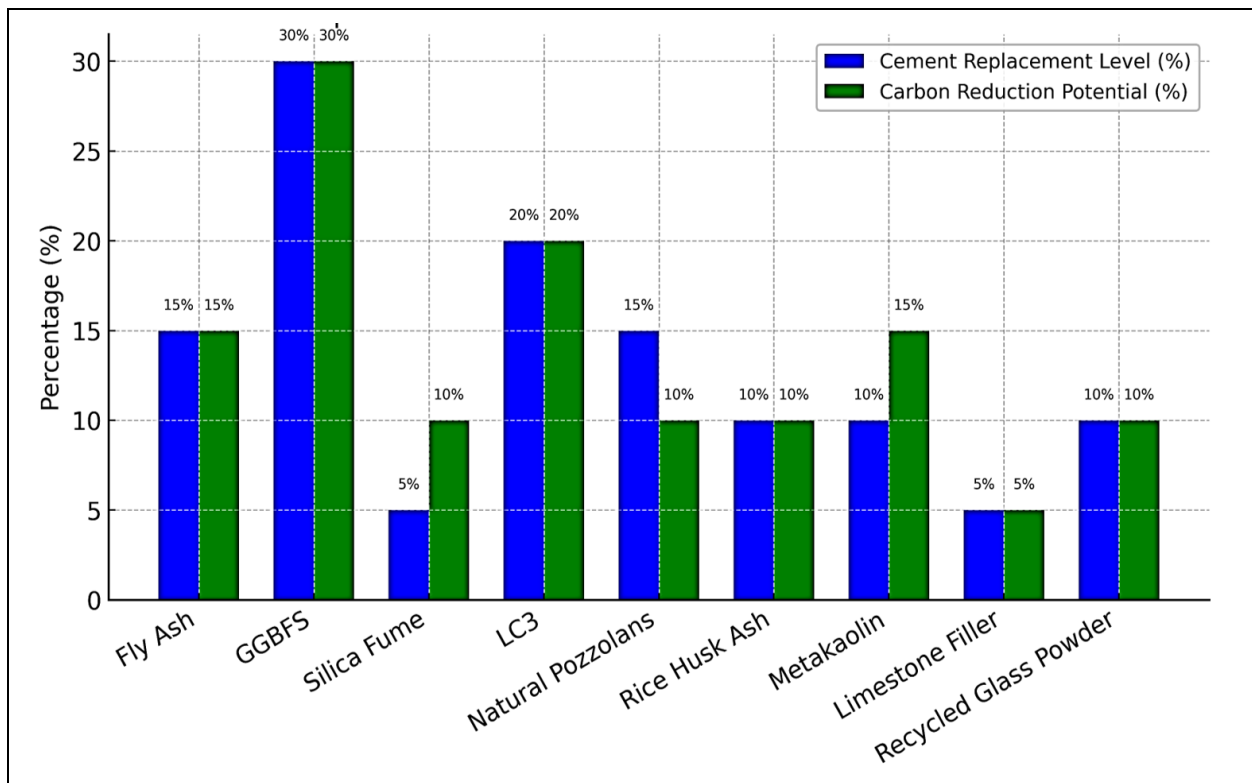


Fig. 5: Histogram displaying the cement replacement level and carbon reduction potential for each SCM

Table 5. Cement replacement level and carbon reduction potential for SCMs

SCM Material	Typical Cement Replacement Level	Carbon Reduction Potential
Fly Ash	15–35%	15–30%
GGBFS	30–50%	30–50%
Silica Fume	5–10%	10–20%
Calcined Clay	20–40%	20–40%
Natural Pozzolans	15–30%	10–25%
Rice Husk Ash	10–20%	10–15%
Metakaolin	10–20%	15–25%
Limestone Filler	5–15%	5–15%
Recycled Glass Powder	10–20%	10–15%

7. GREENHOUSE GAS EMISSIONS

Table 6 quantifies the greenhouse gas (GHG) emissions reduction for various SCMs when replacing 20% of cement in a concrete mixture. Table 6 includes typical GHG emissions for each SCM compared to Portland cement, estimated GHG emissions reduction, and additional benefits. GHG Reduction for 20% Replacement is calculated by comparing SCM emissions with cement emissions for the portion replaced. Supplementary cementitious materials significantly contribute to reducing GHG emissions in concrete production. Fly ash, which has emissions ranging from 5 to 50 kg CO₂ per ton, can replace 20% of Portland cement, leading to a GHG reduction of 15 to 20% while enhancing durability and workability and reducing heat

of hydration (UEPA 2021). Ground Granulated Blast-Furnace Slag has emissions of 50 to 200 kg CO₂ per ton and achieves a reduction of 12 to 20%, improving sulfate resistance and increasing concrete durability. Silica fume, with emissions between 50 and 300 kg CO₂ per ton, provides a GHG reduction of 10 to 15% and enhances strength and durability while reducing permeability. Limestone Calcined Clay cement emits 150 to 300 kg CO₂ per ton and offers a sustainable alternative that reduces shrinkage and enhances early strength, achieving a GHG reduction of 10 to 15%. Natural pozzolans, with emissions of 50 to 200 kg CO₂ per ton, can improve durability and resist chemical attacks, leading to a reduction of 12 to 18% (UEPA 2021). Rice husk ash, which utilizes agricultural waste, has emissions of 50 to 100 kg CO₂ per ton and results in a GHG reduction of 15 to 20%, enhancing durability. Metakaolin has higher emissions of 300 to 400 kg CO₂ per ton, but it increases strength and resists chloride attack, achieving an 8 to 12% reduction (UEPA 2021). Limestone fillers contribute lower emissions of 20 to 50 kg CO₂ per ton, achieving a 10 to 15% reduction while enhancing workability. Lastly, recycled glass powder emits between 50 and 150 kg CO₂ per ton and can reduce landfill waste while providing a GHG reduction of 12 to 18% and improving surface finishes. Overall, incorporating these SCMs helps lower emissions and enhances the performance of concrete. Fig. 6 compares the GHG Emissions for SCM Materials and Portland Cement, with the GHG Reduction for 20% Replacement labelled above each material.

Table 6. Greenhouse gas emissions for various SCMs

SCM Material	GHG Emissions for SCM (kg CO ₂ /ton)	GHG Emissions for Portland Cement (kg CO ₂ /ton)	GHG Reduction for 20% Replacement (%)	Additional Benefits
Fly Ash	5–50	800–900	15–20%	Enhances durability and workability, reduces the heat of hydration
GGBFS	50–200	800–900	12–20%	Improves sulfate resistance, increases concrete durability
Silica Fume	50–300	800–900	10–15%	Increases strength, reduces permeability, enhances durability
Limestone Calcined Clay Cement	150–300	800–900	10–15%	Reduces shrinkage, enhances early strength, sustainable alternative
Natural Pozzolans	50–200	800–900	12–18%	Improves durability, resists chemical attack
Rice Husk Ash	50–100	800–900	15–20%	Utilizes agricultural waste, improves durability
Metakaolin	300–400	800–900	8–12%	Increases strength, reduces permeability, and resists chloride attack
Limestone Filler	20–50	800–900	10–15%	Reduces CO ₂ emissions, enhances workability
Recycled Glass Powder	50–150	800–900	12–18%	Reduces landfill waste, can improve surface finish

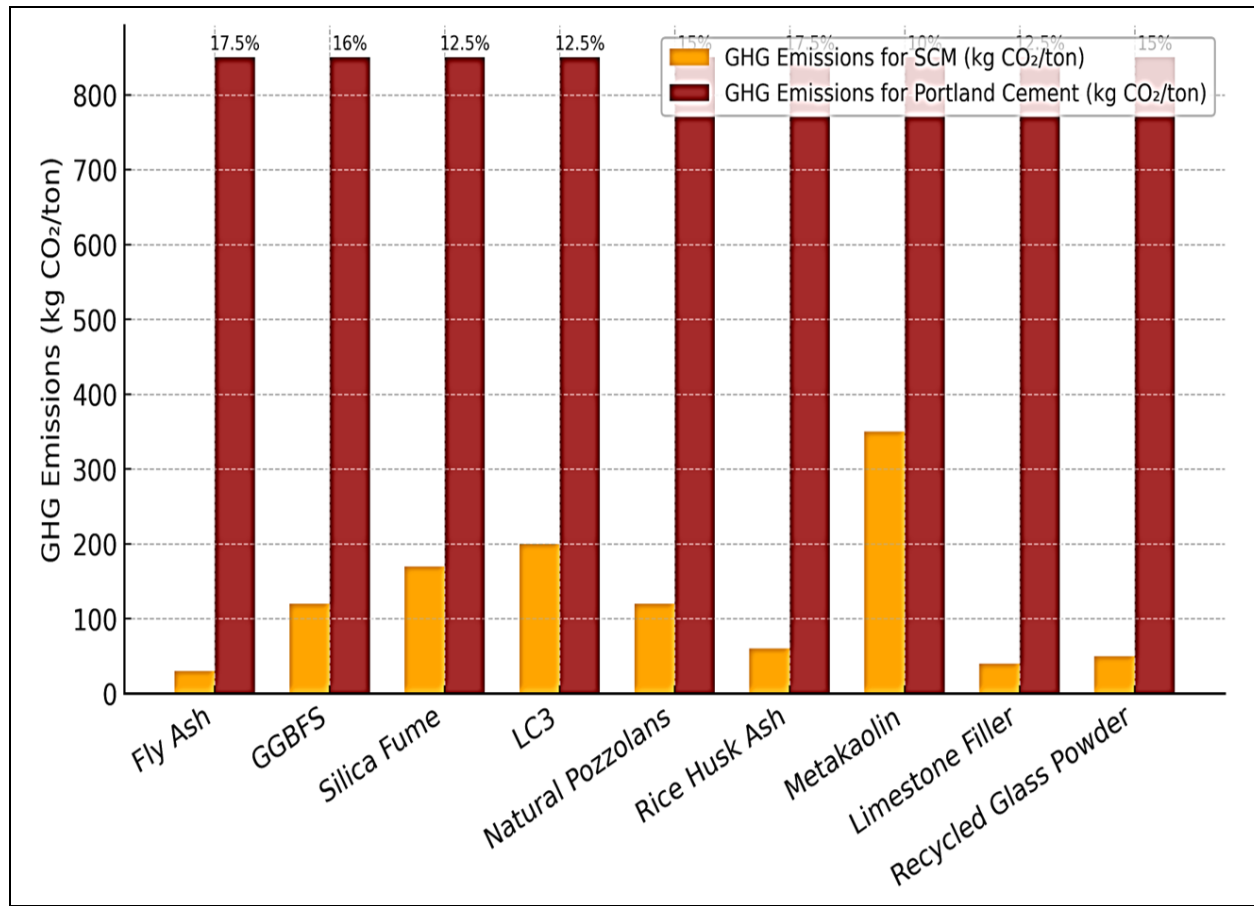


Fig. 6: Comparison of GHG emissions for SCM materials and Portland cement, with the GHG reduction for 20% replacement labelled above each material

8. FRESH PROPERTIES OF LOW-CARBON CONCRETE

Table 7 summarizes the fresh properties of low-carbon concrete, including typical values and comparisons to conventional concrete. Air content and segregation resistance are important for the durability of concrete in various environmental conditions, particularly in freeze-thaw scenarios. Plastic shrinkage and bleeding metrics are critical for the surface quality and integrity of the concrete during the curing process. The viscosity of low-carbon concrete may be adjusted with admixtures to improve pumpability and ensure uniform mixing. Low-carbon concrete exhibits significant improvements in fresh properties over conventional concrete, particularly in areas of workability and durability. The slump range for low-carbon concrete (60–180 mm) is generally higher than that of conventional concrete (50–150 mm), a benefit attributed to the addition of SCMs such as fly ash, which enhances workability. It is highlighted that the density of low-carbon concrete (2200–2400 kg/m³) is typically lower than conventional concrete (2300–2500 kg/m³) due to the use of lighter SCMs and recycled aggregates. Additionally, air content tends to be higher in low-carbon

concrete (5–8% compared to 4–7%), improving resistance to freeze-thaw cycles. Moreover, studies indicate that setting times for low-carbon concrete are extended (initial: 40–80 min; final: 120–240 min), which can be advantageous for workability in warmer climates. Enhanced workability is also noted, with low-carbon concrete achieving Vebe times of 8–20 seconds compared to 5–15 seconds for conventional concrete, due to the addition of superplasticizers and SCMs. Furthermore, low-carbon concrete shows reduced plastic shrinkage (0.005–0.02 mm/m vs. 0.01–0.03 mm/m), effectively lowering the risk of cracking.

According to segregation resistance is generally rated higher in low-carbon mixes than in conventional concrete, promoting uniform material distribution. Bleeding rates are also reduced (0.5–3 L/m²/h for low-carbon vs. 1–5 L/m²/h for conventional concrete), which improves surface finish and durability (Gartner and Hirao, 2015). Viscosity tends to be slightly higher (8–25 Pa·s vs. 5–20 Pa·s), which enhances pumpability during placement. These cumulative benefits position low-carbon concrete as a viable, sustainable alternative in construction, offering both environmental and performance advantages.

Table 7. Comparison of fresh properties of low-carbon concrete with conventional concrete

Fresh Property	Conventional Concrete	Low-carbon Concrete	Notes/Benefits
Slump (mm)	50–150	60–180	SCMs may enhance workability, allowing for higher slumps
Density (kg/m ³)	2300–2500	2200–2400	Lower density may occur due to the use of lighter SCMs or recycled aggregates
Air Content (%)	4–7%	5–8%	Higher air content can improve workability and freeze-thaw resistance
Setting Time (minutes)	Initial: 30–60 Final: 90–180	Initial: 40–80, Final: 120–240	Longer setting times with some SCMs may be beneficial for workability
Workability (Vebe time, sec)	5–15	8–20	Enhanced workability with the addition of superplasticizers and SCMs
Temperature (°C)	20–30	20–30	Fresh concrete temperature generally remains stable; however, low-heat mixes may be cooler
Plastic Shrinkage (mm/m)	0.01–0.03 mm/m	0.005–0.02 mm/m	SCMs can reduce plastic shrinkage, decreasing the risk of cracking
Segregation Resistance	Moderate to high	High	SCMs and additives improve segregation resistance, ensuring uniformity in the mix
Bleeding Rate (L/m ² /h)	1–5	0.5–3	Lower bleeding rates can enhance surface finish and durability
Viscosity (Pa·s)	5–20	8–25	Some low-carbon mixtures may exhibit higher viscosity, improving pumpability

9. PERFORMANCE AND DURABILITY OF LOW-CARBON CONCRETE

Table 8 summarizes the performance and durability characteristics of low-carbon concrete, including various properties, typical values, and comparisons to conventional concrete. Low-carbon concrete demonstrates significant advantages over conventional concrete in terms of strength, durability, and environmental impact. Compressive strength in low-carbon concrete can meet or even exceed that of conventional concrete when appropriate mix designs and curing conditions are applied, along with careful material

selection. Durability is also enhanced through improved resistance to environmental factors, effectively extending the lifespan of structures. The reductions in water absorption and chloride ion penetration contribute to increased resilience against freeze-thaw cycles and corrosion, which further bolsters durability. Additionally, CO₂ emissions are notably lower in low-carbon concrete, largely due to reduced clinker content and the use of SCMs, which makes it an eco-friendlier choice. Finally, the high recyclability of low-carbon concrete materials supports sustainability goals, encouraging the use of waste materials in construction and advancing circular economy practices.

Table 8. Performance and durability characteristics of low-carbon concrete

Property	Conventional Concrete	Low-Carbon Concrete	Notes/Benefits
Compressive Strength	20–40 MPa (varies by mix)	20–50 MPa (with SCMs or alternative binders)	Strength can be achieved using SCMs and optimized mix designs
Durability (Service Life)	50–100 years	70–120 years (with proper design)	Enhanced durability through better material properties
Water Absorption	5–10%	3–7%	Reduced permeability with the use of SCMs improves resistance to water ingress
Sulfate Resistance	Moderate to low	High (especially with GGBFS)	SCMs like GGBFS enhance sulfate resistance, prolonging service life
Chloride Ion Penetration	15–30 mm (high permeability)	5–15 mm (lower permeability)	Better performance against corrosion, reducing maintenance needs
Heat of Hydration	60–70 °C (for large pours)	30–50 °C (with SCMs)	Lower heat generation minimizes thermal cracking
Shrinkage	0.05–0.1 mm/m	0.03–0.06 mm/m	Reduced shrinkage with the use of SCMs like fly ash and metakaolin
CO ₂ Emissions	400–600 kg/m ³	200–300 kg/m ³ (with SCMs)	Significant reduction in carbon footprint through the use of SCMs
Recyclability	80–90% (for aggregates)	90%+ (potentially higher)	Increased use of recycled materials supports the circular economy
Thermal Conductivity	1.5–2.0 W/m·K	1.2–1.8 W/m·K	Lower thermal conductivity may enhance insulation properties

Low-carbon concrete offers substantial improvements over conventional concrete in terms of strength, durability, and environmental impact. While compressive strength in conventional concrete ranges from 20–40 MPa depending on the mix, low-carbon concrete can achieve strengths of 20–50 MPa through optimized mix designs and the use of SCMs, such as fly ash and slag, that enhance material properties. The service life of low-carbon concrete extends to 70–120 years, compared to 50–100 years for conventional concrete, thanks to improved durability from reduced permeability and increased sulfate resistance. For instance, water absorption in low-carbon concrete is reduced to 3–7%, from 5–10% in conventional types, which helps prevent water ingress. SCMs such as GGBFS improve sulfate resistance, prolonging structural service life. Additionally, chloride ion penetration is significantly lower in low-carbon concrete (5–15 mm) compared to 15–30 mm in conventional mixes, which reduces corrosion risk and minimizes maintenance requirements. The heat of hydration for low-carbon concrete is also lower (30–50 °C) than conventional concrete (60–70 °C), reducing the risk of thermal cracking in large pours. With shrinkage values reduced to 0.03–0.06 mm/m (compared to 0.05–0.1 mm/m in conventional concrete), low-carbon concrete exhibits enhanced dimensional stability, especially with SCMs like fly ash and metakaolin. Furthermore, CO₂ emissions are halved, averaging 200–300 kg/m³ compared to 400–600 kg/m³ for conventional concrete, making low-carbon concrete a low-impact option. The recyclability of low-carbon concrete is also high, reaching above 90% due to the increased use of recycled materials, promoting a circular economy (Amran *et al.* 2015). Lastly, the thermal conductivity is slightly lower (1.2–1.8 W/m·K), potentially enhancing insulation properties and

improving energy efficiency in buildings. Collectively, these advantages make low-carbon concrete a more sustainable alternative with superior performance characteristics compared to conventional concrete. Fig. 7 shows a normalized comparison of properties, illustrating relative strengths and improvements in low-carbon concrete across various attributes.

10. MIX PROPORTIONS

Table 9 presents a comparison of the low-carbon-emission concrete mix design with a traditional concrete mix design, quantifying the components, their proportions, quantities, and estimated carbon emissions associated with each. The low-carbon concrete mix achieves a significant reduction in carbon emissions by lowering Portland cement content from 400 kg/m³ to 300 kg/m³, cutting emissions by 25%. The mix includes 250 kg/m³ of fly ash and 150 kg/m³ of GGBFS as SCMs, which replace a portion of the cement and enhance sustainability and performance. Both conventional and low-carbon mixes maintain the same quantities of fine and coarse aggregates, ensuring that the shift to low-carbon concrete does not impact aggregate use. The water-to-cement ratio is also unchanged, with the addition of a small amount of superplasticizer in the low-carbon mix to improve workability without increasing water content. Overall, CO₂ emissions are reduced from 1200 kg CO₂ e/m³ in traditional concrete to 937 kg CO₂ e/m³ in low-carbon concrete, yielding a reduction of 263 kg CO₂ e/m³ (approximately 22%). The low-carbon-emission concrete mix design not only maintains comparable performance characteristics to traditional concrete but also significantly reduces carbon emissions through strategic material choices. The incorporation of supplementary cementitious materials, such as fly ash and GGBFS, plays a crucial role in enhancing the sustainability profile of the concrete mix.

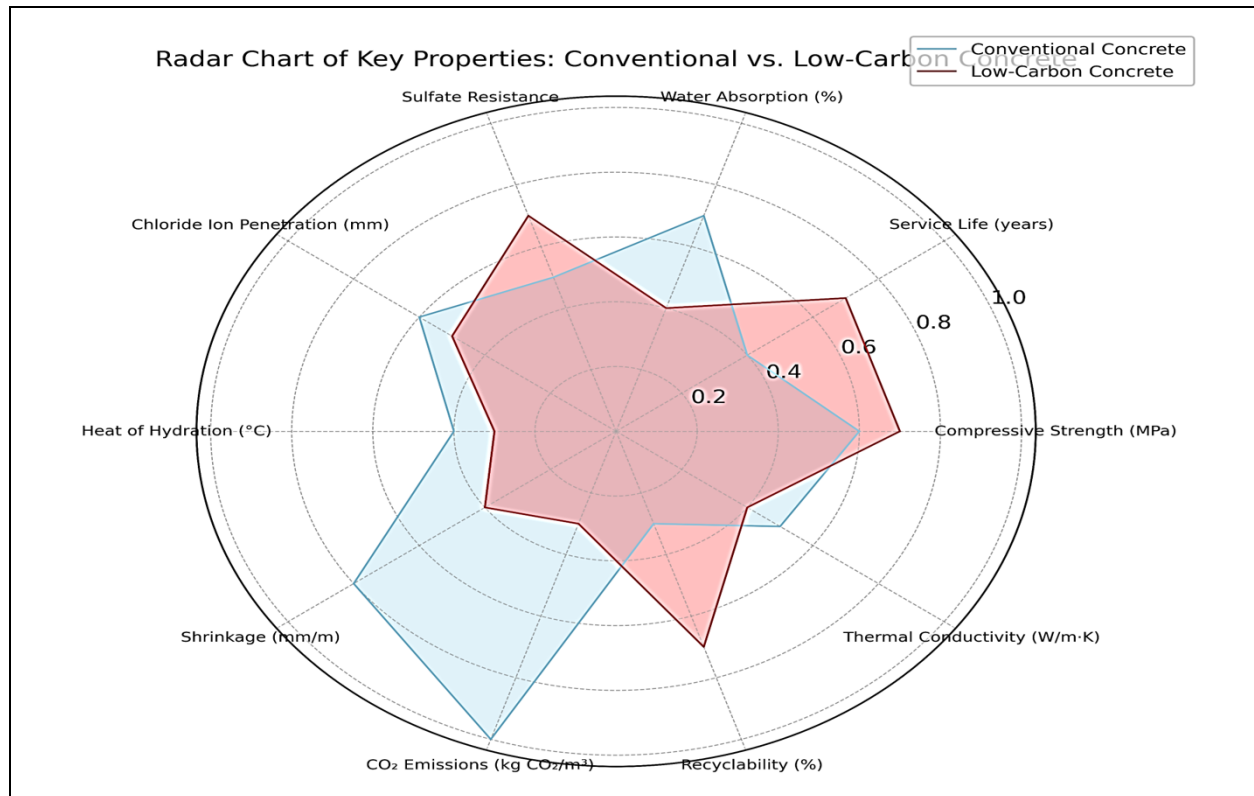


Fig.7: Radar chart with comparison of properties across various attributes

Table 9. Comparison of mix proportions of low-carbon-emission concrete and traditional concrete

Component	Traditional Concrete Mix	Low-Carbon-Emission Concrete Mix	Difference
Cement (Ordinary Portland Cement)	40% (400 kg/m ³)	30% (300 kg/m ³)	-100 kg/m ³ (25% reduction)
Fly Ash (Class F)	0% (0 kg/m ³)	25% (250 kg/m ³)	+250 kg/m ³ (replacement for cement)
GGBFS	0% (0 kg/m ³)	15% (150 kg/m ³)	+150 kg/m ³ (supplementary material)
Fine Aggregate (Sand)	30% (600 kg/m ³)	30% (600 kg/m ³)	No change
Coarse Aggregate (Crushed Stone)	50% (1200 kg/m ³)	50% (1200 kg/m ³)	No change
Water	0.5 (Water-to-cement ratio)	0.5 (Water-to-cement ratio)	No change
Superplasticizer	0% (0 kg/m ³)	1% (3 kg/m ³)	+3 kg/m ³ (improves workability)
Total Mix Design	100% (2550 kg/m ³)	100% (2553 kg/m ³)	+3 kg/m ³ (overall total)
Estimated CO ₂ Emissions	1200 kg CO ₂ e/m ³	937 kg CO ₂ e/m ³	-263 kg CO ₂ e/m ³ (22% reduction)

11. CONCLUSION

1. Low-carbon concrete reduces greenhouse gas emissions by using SCMs and alternative binders.
2. Low-carbon concrete achieves comparable or superior strength and durability, with fly ash and slag improving long-term performance and resistance to sulfates/chlorides.
3. Though initial costs may be higher, lifecycle savings from reduced maintenance and longer service life outweigh the investment.

4. Stricter regulations and codes support the adoption of low-carbon concrete in sustainable construction.
5. Ongoing research and optimized mix designs are key to enhancing sustainability and performance.

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