

Life Cycle Assessment and Cost Analysis of Green Concrete Mixtures for Sustainable Construction Using SimaPro Software

¹Sakshi Pazai, ²Dr. Ketan A. Salunkhe, ³Sachin Pagar

¹Department of Civil Engineering G.N. Sapkal College of Engineering Anjneri Nashik, Maharashtra

²Associate Professor, Dept. of Civil Engineering G.N. Sapkal College of Engineering Anjneri Nashik, Maharashtra

³Assistant Professor, Dept. of Civil Engineering G.N. Sapkal College of Engineering Anjneri Nashik, Maharashtra

Abstract- This study assesses green concrete made by replacing Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash. Experimental tests and life cycle analysis using SimaPro v9 and Ecoinvent show the mixes meet M30 compressive strength while cutting CO₂ emissions, acidification, and resource depletion. Reduced clinker use lowers embodied energy and costs, enhancing economic feasibility. Findings align with global research, confirming technical reliability and sustainability.

Keywords: Green concrete, life cycle assessment, SimaPro, sustainability, supplementary cementitious materials, GGBS, fly ash, circular economy.

I. INTRODUCTION

Context and Motivation

Construction is responsible for about 32% of global natural resource extraction and over 35% of greenhouse gas emissions, largely due to cement production in concrete.(W. Michael et & al. 2016). Innovations in green concrete, including recycled aggregates and industrial by-products, are central to meeting international sustainability targets.(S. John, G. 2023) Recent LCA studies worldwide underscore the pressing need to evaluate not just cradle-to-gate (production) impacts but full lifecycle impacts, including building use and end-of-life scenarios.

Research Problem

Traditional assessments focus mainly on the production phase, while broader environmental categories (acidification, toxicity, resource use) and social aspects (human health, circular economy) are frequently omitted.

Objectives

Quantify and compare structural, environmental, and cost performance of traditional and SCM-based concrete via LCA and LCCA. Place the results in context with international benchmarking studies. Guide the adoption of green concrete mixtures for sustainable practices

Paper Contributions

This study combines a rigorous experimental program with comprehensive LCA/LCCA digital modeling, covering multiple impact categories. The findings are contextualized against recent global research, and practical recommendations for industry are provided.

II. BACKGROUND AND LITERATURE REVIEW

Life Cycle Assessment (LCA) in Civil Engineering

LCA has become the preferred scientific method to holistically analyze construction material environmental impacts. Modern LCA methodology follows ISO 14040/44 and includes four essential stages: goal and scope definition; inventory analysis (LCI); (Panahandeh.2021). impact assessment (LCIA);(. Del, M. N 2017) and interpretation. Global reviews show that attributional LCA (examining the actual environmental footprint) is particularly suitable for concrete studies, whereas consequential LCA is used for policy-based decisions.

Green Concrete: SCMs and Circular Economy

Green concrete leverages not only SCMs (GGBS, fly ash, recycled aggregate) but also promotes the circular economy by repurposing waste and reducing landfill disposal. (B. Baitollah, 2023) Peer-

reviewed comparative LCAs demonstrate that replacing natural aggregates and clinker can lower global warming potential (GWP) by up to 35%.(N. Bairagi 2019).

Recent International LCA Findings

A growing body of evidence supports LCA for optimizing green mix designs: (Knoeri et al.2023) demonstrated 30% lower environmental impact in recycled concrete mixes compared to conventional concrete. A 35% reduction in environmental impact from transporting RCA versus NCA. (Yazdanbakhsh et al.2023). Life cycle impact assessments increasingly include toxicity, human health, and land-use effects (J. Turk, Z. Cotič 2015).

Integration of LCA and LCCA

Lifecycle cost assessment (LCCA) is critical to practical adoption, showing that green concretes can match or lower the total cost of ownership.(J. Turk, Z. Cotič 2015).

III. MATERIALS AND METHODOLOGY

Experimental Design and Data Collection

- Concrete Mixes and Testing

Following IS codes, three M30-grade mix types were studied:

Traditional OPC (control)

GGBS-based (partial OPC replacement)

Fly Ash-based (partial OPC replacement)

All mixes were cast in 150 mm cubes, cured, and tested for compressive strength at 7, 14, and 28 days, in accordance with IS 516.

Materials

Table I details all input materials.

Material	Description
OPC 53	IS 12269
Sand	Zone II, river
Aggregate	20 mm granite
GGBS	IS 12089
Fly Ash	IS 3812, Class F
Water	Potable

Mix Proportions

Table II summarizes composition by mass.

Mix	OPC	GGBS/Fly Ash	Fine Agg.	Coarse Agg.
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Traditional	350	–	750	1200
GGBS	210	140	750	1200
Fly Ash	245	105	750	1200

LCA and LCCA Modeling

LCA Framework

Functional Unit: 1 m³ of concrete

System Boundary: Cradle-to-gate (raw extraction through batching)

LCA Model: SimaPro v9, using Ecoinvent datasets and IMPACT 2002+ for mid-/end-point indicators

LCI capture all energy and material flows with special attention to SCM production, transport, and mixing.(S. G. Al-Ghamdi,2017).

Environmental Indicators

The study assesses multiple categories per popular international convention:

Global Warming Potential (GWP)

Acidification Potential

Resource Depletion (mineral and energy)

Human Health and Toxicity (where data is available)

Life Cycle Cost Model

The LCCA includes all direct input costs (raw, transport, processing) and operational/maintenance costs associated with durability. All parameters were confirmed with market surveys and supplier data (Table III).

IV. RESULTS

Mechanical Properties

All mixes achieved M30 standards. OPC mixes provided the highest early strength (average 33–34 MPa at 28 days), while GGBS and FA mixes reached adequate strengths (30–32 MPa), with slower early-age development. Enhanced durability was noted for mixes with SCMs, consistent with international findings.

Environmental Impact Assessment

LCA Results Overview

Table III LCA Result Overview

Mix	GWP (kgCO ₂ - eq/m ³)	Acidification	Resource Depletion
Traditional	330	High	High
GGBS- based	230	Moderate	Low
Fly Ash	240	Moderate	Low

SCM-based mixes reduced GWP by nearly 30%—a result mirrored in global meta-analyses. Acidification and resource depletion also improved, confirming broader sustainability benefits.

Detailed Environmental Indicators

Where data permits, results can be further disaggregated:

Toxicity Potential (kg 1,4-DCB-Eq): Lower for SCM mixes

Land Use, PM2.5: Both improved in green concrete scenarios

Life Cycle Cost Results

Table IV Life Cycle Cost Result

Component	OPC (₹/m ³)	GGBS (₹/m ³)	Fly Ash (₹/m ³)	% Savings (SCMs)
Raw	4000	3500	3400	12–15%
Cement/SCM	2500/0	1800/800	1700/700	+SCM cost, – overall
Energy	600	500	480	15–20%
Maintenance	3000	2000	2100	30–35%
Total	13000	11150	10980	15–18%

Consistent with Abbas et al., local/by-product SCM use lowered lifecycle costs despite higher procurement or transport per unit.

Comparison with Recent Literature

Peer-reviewed work shows analogous reductions in both CO₂ and lifecycle costs as reported here, especially with partial OPC replacement by GGBS or fly ash. Specific additions (recycled powders, slags,

RCP) further enhance these environmental outcomes in recent studies.

V. DISCUSSION

Environmental and Mechanical Trade-offs

While OPC mixes reach strength targets fastest, their environmental impact is highest. SCM mixes not only meet structural needs but also realize substantial eco-benefits (lower GWP, toxicity, acidification, and land use), as highlighted in other international LCA studies. Proper curing controls any modest lag in early strength.

Human Health and Resource Sustainability

Lower toxic emissions (e.g., PM2.5, 1,4-DCB) improve indoor/outdoor air quality and overall occupational safety. SCMs also reduce pressure on finite mineral resources—a critical global issue.

Industrial Adoption Challenges

Widespread adoption faces challenges: data uncertainty in LCA models, local variations in SCM availability, technical guidelines, and quality control. International benchmarking, such as the LEED v4 credit system, further motivates material innovation and LCA-integrated design.

Recommendations and Future Research

Expand LCA scope to cradle-to-grave for more comprehensive impact coverage
Validate durability benefits in long-term field studies
Develop open LCA inventory databases relevant to emerging economies
Encourage policy and benchmarking based on total lifecycle sustainability

VI. CONCLUSION

This study substantiates that green concrete mixes using SCMs deliver substantial mechanical, environmental, and economic advantages. A 30% reduction in carbon emissions and 15–18% cost savings were evident, in alignment with the latest worldwide research. Comprehensive LCAs using industry-standard tools should be mandated for sustainable project delivery and material certification.

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