Sustainability Assessment of Concrete with Alternative Binders using Life Cycle Tools: Extended Study on GGBS-Based Concrete

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Abstract: The manufacture of Ordinary Portland cement is widely recognised as a significant source of global greenhouse gas emissions, underscoring need for alternative binder systems that reduce environmental burdens without compromising structural performance. This study extends prior sustainability assessments of blended concretes through a detailed experimental and life-cycle-based evaluation of "Ground Granulated Blast Furnace Slag" as a substitute to cement. The research aims to develop and optimise GGBS-based concrete mixes with different replacement levels of OPC to determine the mix proportion that achieves enhanced mechanical and environmental performance. Experimental investigations include mix design formulation, specimen preparation, and compressive strength testing across curing periods. The mechanical results will be integrated with a 'cradle-to-gate' Life Cycle Assessment (LCA) to determine embodied carbon (kg CO_2/m^3) and embodied energy (MJ/m^3) using Microsoft Excel and open-access LCA databases. Through this framework, the study seeks to establish correlations between material composition, mechanical performance, and life-cycle impacts. The findings are expected to provide evidence demonstrating that GGBS substitution mitigates the embodied carbon and energy intensity of concrete production. This work contributes to research related to 'low-carbon' construction materials and supports global sustainability goals.

Keywords: Ground Granulated Blast Furnace Slag; Compressive strength; Embodied carbon; Embodied energy.

Introduction

The production of Ordinary Portland Cement (OPC) contributes significantly to global CO_2 emissions, accounting for nearly 7–8% of total emissions. This highlights the need for sustainable alternatives that reduce environmental impact without compromising structural performance. Ground Granulated Blast Furnace Slag (GGBS), an industrial by-product, offers a promising solution due to its latent hydraulic properties and lower embodied emissions. This study investigates the feasibility of using GGBS as a partial replacement for OPC in M30 concrete, integrating experimental testing with life cycle assessment (LCA) to evaluate both mechanical and environmental performance.

Related work

Previous studies have shown that supplementary cementitious materials (SCMs) such as GGBS and fly ash can significantly reduce the environmental footprint of concrete while maintaining adequate strength [1]–[3]. LCA-based research indicates up to 30% reduction in CO_2 emissions with partial OPC replacement. Experimental studies also confirm that GGBS improves durability and long-term strength, though early-age strength may be slightly reduced. However, limited work combines both mechanical testing and LCA to identify an optimal replacement level, which this study addresses.

Table 1. Comparison with previous studies

	LCA	Strength Analysis	Key Focus
[1]	Yes	No	Environmental impact
[2]	Yes	Yes	SCM-based concrete
[3]	Yes	Yes	GGBS performance
This work	Yes	Yes	Strength+ LCA optimisation

Key Contribution

This study provides an integrated experimental and environmental assessment of GGBS-based concrete. It identifies the optimal replacement level by correlating compressive strength with embodied carbon and energy. The work contributes practical insights for sustainable mix design in structural concrete.

Method, Experiments and Results

Concrete mixes were prepared with 0%, 20%, 30%, and 40% GGBS replacement of OPC. Standard mix design (M30) was followed, and cube specimens were tested for compressive strength at 28 days.

Results showed that all mixes achieved strengths above 30 MPa. The control mix recorded 45.29 MPa, while 20%, 30%, and 40% GGBS mixes achieved 42.8 MPa, 44.49 MPa, and 41.82 MPa respectively. The 30% replacement level showed strength comparable to conventional concrete.

LCA (cradle-to-gate) was performed to evaluate embodied carbon and energy. Results indicated significant environmental benefits, with up to 36% reduction in CO_2 emissions and 27% reduction in embodied energy at higher GGBS levels. The 30% mix achieved ~27% CO_2 reduction with minimal strength loss.

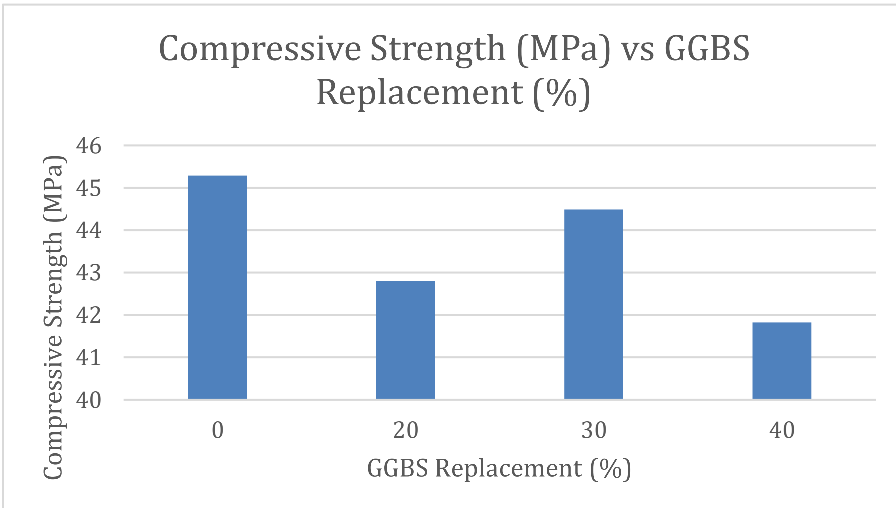


Figure 1. Compressive Strength vs GGBS%

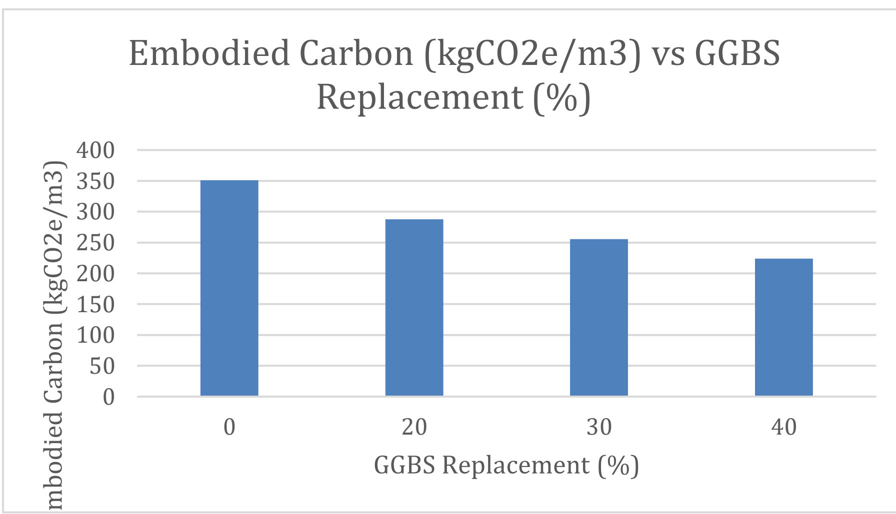
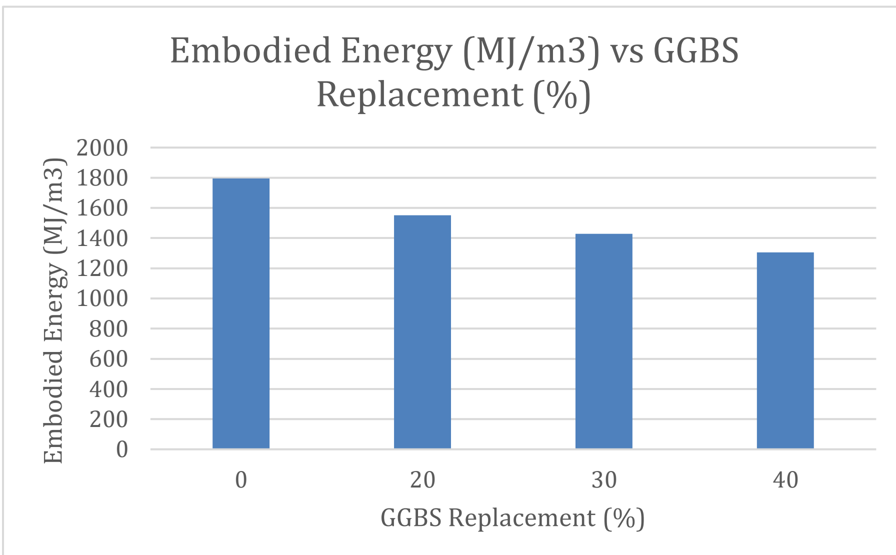


Figure 2. Embodied Carbon vs GGBS%
Figure 3. Embodied Energy vs GGBS%

Discussions

The results demonstrate that GGBS improves sustainability without significantly compromising strength. While higher replacement levels reduce strength slightly, they offer greater environmental benefits. The 30% replacement level provides the best balance between performance and sustainability. Cement clinker was identified as the major contributor to emissions, confirming that binder substitution is key to reducing concrete's carbon footprint.

Conclusions



- Problem Statement: High CO_2 emissions from OPC-based concrete
- Method Used: Experimental testing + cradle-to-gate LCA
- Key Findings:
    - All mixes satisfied M30 strength requirements
    - 30% GGBS is the optimum replacement level
    - Up to 36% reduction in embodied carbon achieved
- Limitations & Future Work:
    - Limited to 28-day strength and cradle-to-gate LCA
    - Future work should include durability and full life-cycle analysis

References

1. L. K. Turner and F. G. Collins, "Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete", Construction and Building Materials, vol. 43, pp. 125–130, 2013.
2. K. Bhagath Singh and K. V. L. Subramaniam, "Environmental and cost performance of concrete containing fly ash and ground granulated blast furnace slag", Journal of Cleaner Production, vol. 448, p. 141729, 2024.
3. B. Ali, M. H. E. Ouni and R. Kurda, "Life cycle assessment of concrete incorporating ground granulated blast furnace slag", Environmental Science and Pollution Research, vol. 29, no. 55, pp. 83580–83595, 2022.
4. A. M. Rashad, "A comprehensive overview about the influence of ground granulated blast furnace slag on concrete properties", Construction and Building Materials, vol. 170, pp. 272–288, 2018.
5. R. Siddique and M. I. Khan, Supplementary Cementing Materials. Berlin, Germany: Springer, 2011.
6. Rahman, Muhammad K., et al. "Development of water-cured alkali-activated concrete with a high volume of silica-rich waste limestone powder and GGBS and Fly ash materials: strength, durability, and life cycle assessment." Journal of Materials in Civil Engineering 37.1 (2025): 04024448.
7. Singh, Rudra Pratap, et al. "Fly ash, GGBS, and silica fume based geopolymer concrete with recycled aggregates: Properties and environmental impacts." Construction and Building Materials 378 (2023): 131168.
8. Ashwini, R. M., Kanaka Durga Sambhana, and M. Manjunatha. "Synergistic effects of Nano-TiO_2 in GGBS-based low-clinker concrete: Mechanical performance, microstructural evolution, and life cycle assessment." Next Materials 11 (2026): 101827.
9. Ali B, Ouni MH, Kurda R. Life cycle assessment (LCA) of precast concrete blocks utilizing ground granulated blast furnace slag. Environmental Science and Pollution Research. 2022 Nov;29(55):83580-95.
10. Askari DF, Shkur SS, Mohammed AA, Mahmood HF, Ali BH, Ahmad SA. Assessing the impact of pozzolanic materials on the mechanical characteristics of UHPC: analysis, and modeling study. Discover Civil Engineering. 2025 May 20;2(1):96.
11. Sharma N, Seema, Paruthi S, Khan AH, Almalki A, Zeyad AM, El-Abbasy AA. Advancing GGBS geopolymer concrete with nano-alumina: A study on strength and durability in aggressive environments. Reviews on Advanced Materials Science. 2025 Sep 4;64(1):20250142.
12. Paruthi S, Raghav YY, Kumari P, Kumar Tipu R, Sharma N. AI based predictive modelling for compressive strength of metakaolin-based geopolymer concrete incorporated with Nano Titanium. Journal of structural integrity and maintenance. 2025 Jul 3;10(3):2503027.
13. Huang Z, Zhou H, Miao Z, Tang H, Lin B, Zhuang W. Life-cycle carbon emissions (LCCE) of buildings: implications, calculations, and reductions. Engineering. 2024 Apr 1;35:115-39.
14. Sun B, Ye G, De Schutter G. A review: Reaction mechanism and strength of slag and fly ash-based alkali-activated materials. Construction and Building Materials. 2022 Apr 4;326:126843.
15. Nasir M, Mahmood AH, Bahraq AA. History, recent progress, and future challenges of alkali-activated binders–An overview. Construction and Building Materials. 2024 May 3;426:136141.