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Sustainable and Green Building Materials: Performance and Embodied Carbon of Low-Clinker Binder Systems

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ABSTRACT

The production of ordinary Portland cement is a major contributor to anthropogenic carbon dioxide emissions, and the construction sector is therefore under increasing pressure to adopt lower-carbon material systems. This paper examines the mechanical performance and embodied carbon of concrete produced with partial and full replacement of clinker by supplementary cementitious materials. Mixes incorporating fly ash and ground granulated blast-furnace slag at several replacement levels were compared with a control mix, together with an alkali-activated geopolymer binder. Compressive and flexural strength were evaluated alongside an estimate of embodied carbon per unit volume. The results show that moderate replacement levels retain acceptable strength while reducing embodied carbon appreciably, and that the geopolymer system achieves the largest reduction. The study argues that material selection for sustainable construction should weigh strength development, durability, and carbon intensity jointly, and that supplementary cementitious materials offer a practical pathway to lower-impact concrete within existing construction practice.

KEYWORDS: *Green building materials, Embodied carbon, Supplementary cementitious materials, Fly ash, Ground granulated blast-furnace slag, Geopolymer, Sustainable concrete*

INTRODUCTION

Buildings and construction together account for a significant share of global energy use and carbon emissions, with cement production alone responsible for a substantial fraction of industrial carbon dioxide (10). As urbanisation continues, the demand for concrete is expected to rise, intensifying the need for materials that deliver structural performance at a reduced environmental cost (6).

Ordinary Portland cement derives much of its carbon footprint from the calcination of limestone and the high temperatures required for clinker production (7). Partial replacement of clinker with industrial by-products such as fly ash and ground granulated blast-furnace slag is a well-established means of reducing this footprint while utilising waste streams (3).

This study evaluates the strength and embodied carbon of binder systems with varying clinker content, including an alkali-activated geopolymer that avoids Portland cement entirely (4). The aim is to clarify the trade-off between mechanical adequacy and carbon reduction across a realistic range of mixes.

LITERATURE REVIEW

Research on supplementary cementitious materials has matured considerably, establishing that pozzolanic and latent-hydraulic additions modify both the fresh and hardened properties of concrete. Fly ash typically improves workability and long-term strength while slowing early strength gain, whereas slag enhances durability in aggressive environments (8). Alkali-activated binders have attracted growing interest as a route to near-zero-clinker concrete (4).

Environmental Drivers of Material Substitution

The motivation for substituting clinker is reinforced by several converging pressures within the construction sector:

- Regulatory and voluntary commitments to reduce embodied carbon in buildings (10).
- The availability of fly ash and slag as by-products requiring beneficial use (3).
- Durability benefits associated with refined pore structure in blended systems (8).
- Rising interest in life-cycle rather than purely operational carbon accounting (9).

Despite these drivers, concerns regarding early-age strength, curing sensitivity, and consistency of by-product quality continue to influence the extent of adoption in practice (5).

RESEARCH GAP

While the individual effects of fly ash, slag, and geopolymer binders are documented, direct comparisons that report both mechanical performance and embodied carbon for a consistent set of mixes are less common. Many studies emphasise strength or durability without quantifying the associated carbon reduction, making it difficult for designers to judge the overall benefit. A combined assessment is needed to support evidence-based material selection.

OBJECTIVES

- To prepare concrete mixes with fly ash and slag at several replacement levels alongside a control mix.
- To evaluate the compressive and flexural strength of each mix.
- To estimate the embodied carbon per unit volume for each binder system.
- To compare the strength-to-carbon trade-off across conventional and alkali-activated binders.

METHODOLOGY

Concrete mixes were proportioned for a target characteristic strength using a constant water-to-binder ratio, with cement replaced by fly ash or slag on a mass basis (2). A geopolymer mix based on fly ash activated by an alkaline solution was also prepared. Specimens were cured under standard conditions and tested at fixed ages (1).

Materials and Mix Proportions

The binder combinations and key constituent proportions are listed in Table 1. Locally available river sand and crushed aggregate were used across all mixes to isolate the effect of the binder. The replacement levels were chosen to span the range commonly permitted in practice and to include a high-volume case for each addition (3, 5).

Table 1: Binder combinations and constituent proportions of the mixes

Mix	Cement (%)	Fly ash (%)	GGBS (%)	Notes
Control (OPC)	100	0	0	Reference mix
FA-20	80	20	0	Low fly ash
FA-40	60	40	0	High fly ash
GGBS-50	50	0	50	Slag blend
GGBS-70	30	0	70	High slag
Geopolymer	0	100*	0	*Alkali-activated

Testing and Embodied Carbon Estimation

Compressive strength was determined on cube specimens and flexural strength on prisms at standard ages. Embodied carbon was estimated by multiplying the mass of each constituent by published carbon coefficients and summing the contributions per cubic metre (6, 9). The approach captures cradle-to-gate emissions associated with material production and is consistent with common practice in comparative studies.

RESULTS AND FINDINGS

The embodied carbon of the binder systems is presented in Figure 1, which shows a progressive reduction as clinker content decreases. The mechanical performance of the corresponding mixes is reported in Table 2, enabling the strength and carbon outcomes to be considered together.

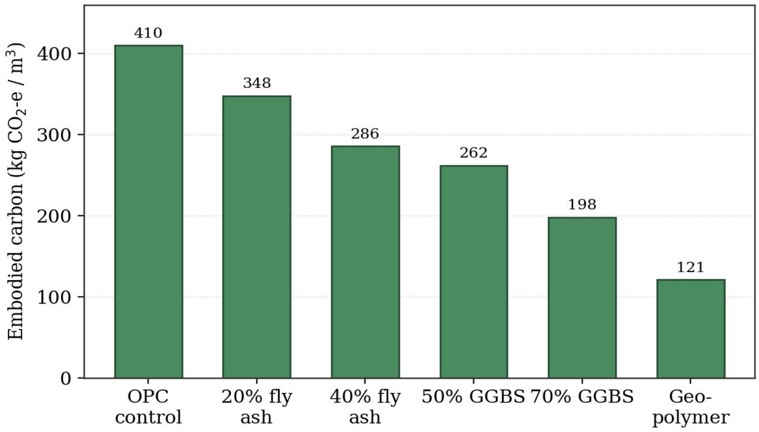

Figure 1: Embodied carbon of the binder systems evaluated in the study

Embodied carbon fell steadily with increasing replacement, and the geopolymer system recorded the lowest value owing to the absence of Portland clinker. The strength results show that moderate replacement preserves most of the control strength, whereas very high replacement levels reduce early strength and require attention to curing.

Table 2: Strength and embodied carbon of the concrete mixes

Mix	28-day compressive (MPa)	Flexural (MPa)	Embodied carbon (kg CO2-e/m3)
Control (OPC)	41.2	4.6	410
FA-20	39.5	4.4	348
FA-40	34.8	4.0	286
GGBS-50	38.1	4.3	262
GGBS-70	33.6	3.9	198
Geopolymer	36.4	4.1	121

DISCUSSION

The results demonstrate a clear inverse relationship between clinker content and embodied carbon, consistent with the dominant role of cement in the carbon profile of concrete (7, 10).

Moderate fly ash and slag replacement reduced embodied carbon by a meaningful margin while retaining strength close to the control, indicating that such mixes can be adopted with limited compromise in many applications (3).

High-volume replacement produced larger carbon savings but at the expense of early strength, reflecting the slower reaction of fly ash and the curing sensitivity of slag-rich systems (5, 8). The geopolymer binder achieved the greatest carbon reduction while maintaining adequate strength, although its dependence on activator chemistry and curing conditions remains a practical consideration (4).

Taken together, the findings support a material-selection logic that considers carbon intensity alongside strength and durability rather than treating them in isolation (6, 9). For routine construction, moderate replacement offers a low-risk reduction in embodied carbon, while geopolymer systems represent a promising option where supply chains and quality control permit.

CONCLUSION

This investigation compared the mechanical performance and embodied carbon of concrete produced with varying clinker content. Replacement of cement by fly ash and slag reduced embodied carbon progressively, with moderate replacement levels retaining strength comparable to the control mix. The alkali-activated geopolymer binder delivered the largest carbon reduction while achieving acceptable strength.

The study reinforces the case for supplementary cementitious materials as a practical route to lower-carbon concrete within existing construction practice. Material selection for sustainable building should be guided by the combined assessment of strength development, durability, and embodied carbon, allowing designers to balance environmental and structural objectives.

LIMITATIONS

- Embodied carbon was estimated from published coefficients rather than project-specific data.
- Durability indicators such as chloride penetration and shrinkage were not measured.

- Only one water-to-binder ratio was investigated.
- Variability in the quality of by-products across sources was not addressed.

FUTURE SCOPE

- Long-term durability testing of high-volume replacement and geopolymer mixes.
- Inclusion of transport and construction stages in a full life-cycle assessment.
- Optimisation of activator dosage and curing for geopolymer systems.
- Field trials of low-carbon mixes in structural elements.

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