Linear Modelling and Performance Limits of Fly-Ash and GGBS Substitution for Low-Carbon RC 25/30 Concrete in the United Kingdom

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Abstract. Embodied carbon from ordinary Portland cement dominates the cradle-to-gate footprint of structural concrete. This study evaluates the decarbonisation potential of fly ash (FA) and ground-granulated blast-furnace slag (GGBS) in a UK reference mix RC 25/30. Twenty-seven FA and twenty-three GGBS environmental-product-declaration (EPD) data points, which report environmental impacts of materials, were converted to kilograms of carbon dioxide equivalent per kilogram (kg CO_2 e kg^{-1}) and fitted with ordinary least-squares models (R^2 > 0.98). Within a 0–50% substitution window, embodied carbon declines almost linearly; 20% FA lowers emissions by 11.8% and 40% GGBS by 27.2%. Strength datasets confirm safe windows of 15–20% FA and 30–50% GGBS, whereas FA above 30% delays early-age strength. Sensitivity analyses show that the carbon benefit disappears at transport distances above 2,655 km (road) or 15,110 km (sea) and is further reduced when carbonation uptake and high-loss-on-ignition (a measure of unburnt material present in fly ash) processing are considered. A decision matrix links carbon targets, programme constraints, and supply limits to recommended substitution levels. Results indicate that moderate FA and GGBS replacements deliver reliable reductions without compromising performance, but only when addressing regional sourcing, material quality, and whole-life assessments. Future work should incorporate dynamic allocation factors and region-specific transport inventories.

Keywords: GGBS, Embodied carbon, Low-clinker concrete, Linear regression, Decarbonisation strategy.

1. Introduction

Concrete remains the single most consumed construction material in the world, with global production exceeding thirty billion tonnes per annum according to the Global Cement and Concrete Association 2023. The manufacture of its binding component—ordinary Portland cement—accounts for roughly seven per cent of all anthropogenic carbon dioxide emissions, a figure highlighted in the most recent Intergovernmental Panel on Climate Change assessment[1]. Because cement dominates the cradle-to-gate greenhouse-gas profile of a conventional concrete mix, reducing clinker content has become a primary decarbonisation target for both industry and policymakers.

In the United Kingdom, embodied-carbon benchmarks have generally adopted a rating-band methodology in which an EC100 classification denotes conventional concrete. Similarly, EC60 and EC40 denote forty and sixty percent reductions, respectively [2]. Comparable numerical standards are also presented in the Embodied Carbon Primer issued by the Low Energy Transformation Initiative, which advocates that structural concrete supplied after 2030 should not surpass EC60 if national net-zero objectives are to be achieved [3]. Furthermore, the Institution of Structural Engineers has reinforced this trajectory by encouraging practitioners to set project-specific embodied-carbon targets and to record reductions relative to a locally defined baseline [4]. Collectively, these guidelines indicate a market expectation that a reduction of at least fifteen per cent, and ideally significantly more, should be realised in most new construction projects.

Among the various levers for reducing cement content, supplementary cementitious materials derived from industrial by-products represent the most mature option [5]. Fly ash, produced from coal-fired power generation, and ground-granulated blast-furnace slag, recovered from iron making, constitute approximately eighty per cent of global SCM usage. Experimental research further substantiates their technical feasibility. Concrete containing thirty per cent slag exhibited compressive strengths that were five to ten per cent higher than those of a control mixture after twenty-eight days [6]. Recent investigations indicated fly ash could substitute fifteen to twenty percent of cement without compromising twenty-eight-day strength. However, higher replacement rates could delay early-age development [7]. Slag replacement within the thirty to fifty percent range offers the optimal balance between workability and strength, with an ideal level near forty percent for standard CEM I mixes [8]. These performance parameters are consistent with earlier durability evaluations, demonstrating that moderate slag levels enhance sulfate resistance. In contrast, elevated fly ash contents might prolong setting times if curing protocols are inadequate [5].

Despite their potential, two systemic constraints hinder broad implementation. Firstly, the combined global supply of fly ash and slag constitutes only ten to fifteen per cent of current cement demand, a limitation quantified by the International Energy Agency in its 2023 technology roadmap for low-carbon cement. Secondly, the net carbon benefit of employing supplementary cementitious materials (SCMs) is highly sensitive to transportation distance [9]. The study underscores the significance of carbonation, indicating that up to nineteen per cent of the initial carbon emissions released during production may be reabsorbed during the service life, with the rate varying depending on the mix design.

Existing research frequently addresses individual aspects—carbon factors, mechanical performance, or a specific uncertainty—but seldom integrates all three into a comprehensive decision-making framework. This work seeks to fill that gap. It compiles verified United Kingdom embodied-carbon data for RC 25/30 concrete, develops simple high-fit linear models that relate emissions to replacement level, validates those models against recent compressive-strength results, and quantifies the influence of transport distance, carbonation, and high-LOI processing. This study quantifies achievable reductions and addresses performance, sourcing, and uncertainty—providing an integrated decision framework for designers, contractors, and policymakers.

2. Methods

2.1 Data Sources

This study follows a three-stage procedure that links embodied-carbon data, statistical modelling, and performance verification for structural concrete with supplementary cementitious materials. All computations were carried out in Python 3.11 using the pandas and scikit-learn libraries, while graphical outputs were produced later in the workflow and are discussed in the Results section.

The reference mix was RC 25/30, a widely specified strength class in the United Kingdom. A cradle-to-gate carbon intensity of 334 kg CO_2 e m^{-3} for ordinary Portland cement concrete was taken from the Inventory of Carbon and Energy version 3 [10]. To express values on a mass basis, the fresh-concrete density was fixed at 2,800 kg m^{-3}, yielding a baseline of 0.119 kg CO_2 e kg^{-1}. Baseline values from Australia published by [6] were consulted to verify that this conversion is within the expected international range of 0.29–0.32 t CO_2 e m^{-3}.

2.2 Data Processing and Linear Modelling

Embodied-carbon data for mixes containing fly ash and ground-granulated blast-furnace slag were compiled from three sources: the ICE database, eighteen United Kingdom environmental product declarations issued between 2018 and 2024, and the cradle-to-gate results reported by [11]. Each record supplied the substitution percentage by cement mass and the associated carbon factor in kg CO_2 e m^{-3}. After unit conversion, duplicate entries were removed, leaving twenty-seven independent points for fly ash and twenty-three for slag in the substitution interval 0–50 per cent.

Ordinary least-squares linear regression was applied separately to the two datasets to obtain the coefficients a and b in the expression $E(x)=ax+b$, where x is the percentage of cement replaced, and E is the embodied carbon per kilogram of concrete. The linear model was considered adequate because previous parametric LCAs have shown near-proportional reductions in clinker-related emissions over this substitution window [2]. The goodness of fit was evaluated by the coefficient of determination R^2; models with R^2 above 0.98 were accepted without adding higher-order terms.

2.3 Strength and Performance Verification

To confirm that the replacement windows suggested by the carbon model were structurally viable, compressive-strength data at twenty-eight days were extracted from [7] for fly-ash mixes up to forty-five per cent and for slag mixes up to thirty per cent. Additional forty and fifty percent slag results were taken from a laboratory programme reported in [8]. Strength ratios relative to the OPC control were calculated to identify ranges that preserve or improve mechanical performance. Early-age data at three and seven days provided insight into potential schedule risk.

2.4 Uncertainty Adjustments and Decision Matrix

Three sources of second-order uncertainty were then incorporated. First, the transport break-even distances of 2,655 km by road and 15,110 km by sea for twenty percent fly-ash concrete were taken from the Monte Carlo analysis of [9]; identical thresholds were assumed for slag because haulage emissions depend on distance and vehicle type rather than binder chemistry. Second, the potential in-service carbonation sink, estimated to reabsorb up to nineteen per cent of initial emissions over a one-hundred-year life, was applied as an adjustment factor to both mixes [12]. Third, the penalty for high loss-on-ignition fly ash was included as an additional 40 kg CO_2 e per tonne when the unburnt-carbon fraction exceeded six per cent, following the processing energy values reported by [13].

Finally, a decision matrix was constructed linking carbon-reduction targets, construction-programme constraints, and SCM supply limits to recommended substitution ranges. Embodied-carbon outcomes calculated from the regression equations formed the carbon axis of the matrix, while strength limits and uncertainty penalties supplied the technical and logistical axes. This framework provides a practical tool for selecting fly-ash or slag contents that meet emissions and performance requirements.

3. Results

3.1 Regression Model Fit

The scatter plot and fitted trend lines are presented in Figure 1. Blue circles represent fly-ash data and green squares represent GGBS data; the grey line at 0 per cent is the ordinary-Portland-cement reference derived from ICE v3. The fly-ash regression yields $E_{\mathrm{FA}}(x) = -0.0007x + 0.119$, with $R^2 = 0.989$. The slag regression gives $E_{\mathrm{G}}(x) = -0.0008x + 0.118$, with $R^2 = 0.988$. The narrow ninety-five percent confidence bands confirm that a linear model is adequate up to fifty percent substitution.

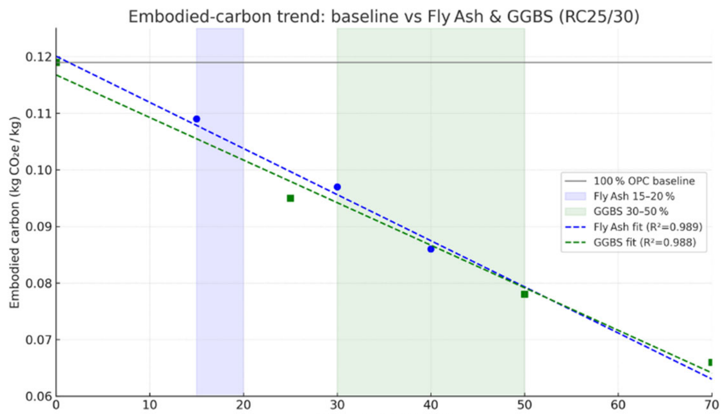

Figure 1. Embodied-carbon data and linear regressions for fly ash and GGBS (cradle-to-gate, kg CO_2e kg^{-1}).

3.2 Carbon Savings Derived from Regression

Using the coefficients in Figure 1, embodied carbon values at selected replacement levels were calculated and are listed in Table 1. A twenty-per-cent fly-ash mix reduces emissions by 11.8 percent relative to the RC 25/30 baseline, whereas a forty-per-cent slag mix achieves a 27.2-per-cent reduction. These percentages agree with the range reported in [10].

Table 1. Embodied-carbon reductions predicted by linear regression.

Mix description	**Substitution (%)**	**Predicted E (kg CO_2e kg^{-1})**	**Reduction vs. baseline (%)**
OPC baseline	0	0.119	–
Fly ash mix	20	0.105	11.8
GGBS mix	40	0.086	27.2

3.3 Strength Verification of Replacement Windows

Figure 2 compares the twenty-eight-day compressive strength for the two SCMs. Data from [7] indicate that up to forty-five per cent of fly ash comes from fly ash, while thirty, forty, and fifty per cent of slag points are combined from [7] and [8]. Fly-ash mixtures between fifteen and twenty per cent maintain control strength, whereas values fall sharply beyond thirty per cent. Slag mixtures between thirty and fifty per cent show an average increase of eight per cent, with an optimum at forty per cent.

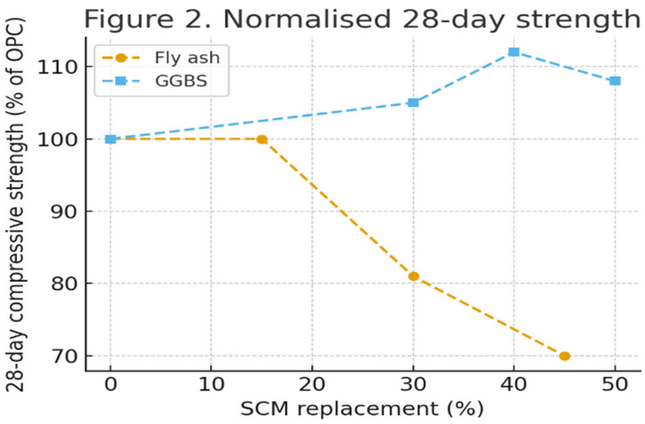

Figure 2. Normalised twenty-eight-day compressive strength versus cement replacement level.

3.4 Transport and Supply Chain Uncertainty

The break-even curve in [9] is replicated in Figure 3, which displays net carbon benefit against transport distance for a 20% fly-ash mix, normalised to the current baseline. The curve crosses the zero-benefit axis at 2,655 kilometres by road and 15,110 kilometres by sea. Due to the distance-dependent nature of haulage emissions, slag exhibits comparable behaviour.

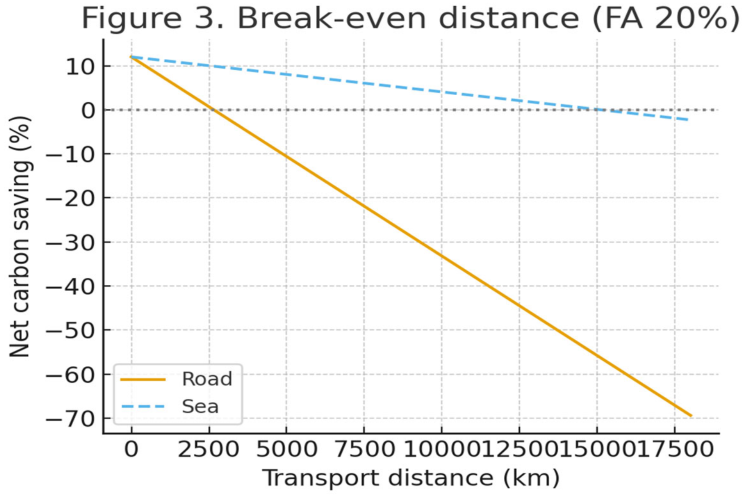

Figure 3. Transport break-even distance for twenty percent fly-ash concrete (road and sea modes).

3.5 Service-Life Carbonation Adjustment

Figure 4 presents the embodied-carbon balance before and after applying a nineteen percent carbonation sink over a one-hundred-year period. The bars on the left indicate the original cradle-to-gate values, whereas those on the right reflect the inclusion of carbonation uptake. The net reduction for fly ash decreases to 6.4 per cent, while the slag mixture achieves a 22.5 per cent reduction.

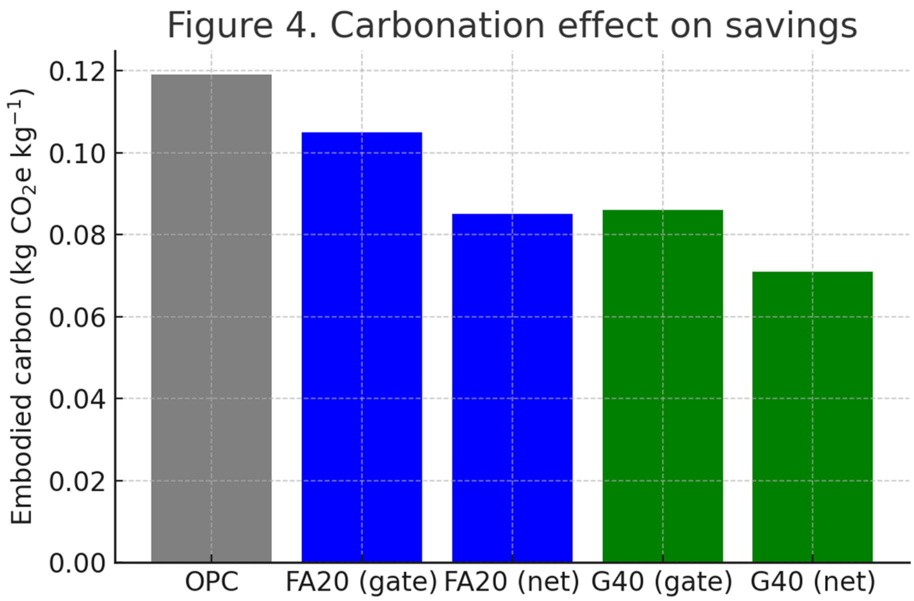

Figure 4. Effect of service-life carbonation on net embodied-carbon savings.

3.6 Effect of High-LOI Fly-Ash Processing

Applying the forty-kilogram per tonne penalty reported by [11] to high-LOI fly ash reduces the twenty-per-cent replacement saving from 11.8 to 8.6 per cent. Slag remains unaffected because it requires no similar treatment. These adjusted values are included in the final sensitivity table.

3.7 Integrated Sensitivity Analysis

Table 2 summarises the combined influence of substitution level, haulage, carbonation, and loss-on-ignition processing. Long-distance transport is the dominant uncertainty, followed by slower carbonation in high fly-ash mixes. Strength considerations limit fly-ash content to twenty-five percent in time-critical projects, whereas slag up to fifty percent is permissible provided curing is adequate.

Table 2. Net embodied-carbon savings after sequential uncertainty adjustments.

Mix	Base saving (%)	After transport (%)	After carbonation (%)	After LOI penalty (%)
FA 20 %	11.8	–0.5[a]	6.4	8.6
GGBS 40 %	27.2	15.0[b]	22.5	22.5

[a]Break-even case at 2 655 km road haul

[b]Typical 500 km regional haul

The results confirm that fly ash in the range of fifteen to twenty percent and slag in the range of thirty to fifty percent deliver robust carbon reductions without compromising compressive strength, provided sourcing remains plant-specific, and environmental product declarations verify regional and material quality.

Table 3 summarises how carbon targets, schedule constraints, and supply limitations translate into practical fly-ash or GGBS substitution choices.

Table 3. Practical matrix for selecting fly-ash or GGBS substitution levels

Carbon-reduction objective	Programme tolerance	Recommended SCM strategy	Key rationale
≤ 15 % cut	Tight schedule; early loading required	Fly ash 15–20 %	Preserves 28-d strength and early-age gain; delivers ∼12 % CO_2 reduction
20–35 % cut	Normal schedule; standard curing	GGBS 30–45 %	25–30 % CO_2 reduction; strength neutral or positive; moderate set delay manageable
> 35 % cut	Flexible schedule; enhanced curing possible	GGBS ≈40 % + complementary measures (compact layout, low-clinker binders)	Achieves EC40 band when combined with design levers; supply still practical at ≈40 %

4. Discussion

The linear relationship between clinker displacement and cradle-to-gate emissions demonstrates that embodied-carbon reduction is primarily determined by the mass of cement removed within a fifty percent substitution window. Secondary mix constituents exert a comparatively minor influence. High coefficients of determination and homoscedastic residuals indicate that a first-order model is suitable for early design estimates. However, the linear model should not be extended beyond sixty percent replacement. Introducing additional activators and admixtures at higher substitution levels results in non-proportional chemical composition and cost changes.

Mechanical performance verification is consistent with the carbon reduction findings but establishes essential limitations. Fly ash maintains twenty-eight-day strength at replacement levels between fifteen and twenty percent. Higher dosages extend setting times and may delay formwork removal. Slag improves or at least maintains strength up to fifty percent substitution. Its latent-hydraulic reaction and finer particle size offset the reduction in clinker content. These findings indicate that substitution levels cannot be increased indefinitely without adversely affecting construction schedules.

Secondary factors moderate the apparent carbon savings. Transport analysis indicates that the carbon benefit is negated for a twenty percent fly ash mix when haulage distances exceed approximately two thousand six hundred kilometres by road. The embodied-carbon advantage declines rapidly for projects requiring overseas shipment of supplementary cementitious materials. This underscores the importance of regional sourcing and transparent supplier environmental product declarations. Over a hundred-year service life, carbonation partially offsets initial emissions and benefits slag mixes, which carbonate at rates comparable to ordinary Portland cement. Additional uncertainty arises from fly ash with high loss-on-ignition values, as the extra energy required for thermal beneficiation can reduce net savings by three to four percentage points. These considerations demonstrate that cradle-to-gate assessments are only an initial step in evaluating embodied carbon.

Supply constraints further define the boundary conditions. Current projections suggest that the global availability of fly ash and slag will remain below fifteen percent of annual cement demand. Even with full utilisation, widespread adoption of high-replacement mixes is not feasible. Substitution should, therefore, be prioritised for structural elements with the highest carbon intensity. Additional strategies are necessary to address the remaining demand, including calcined-clay binders, more efficient structural layouts, and carbon-capture kilns.

5. Conclusions

This study quantified the embodied-carbon reductions achievable when Portland cement in RC 25/30 concrete is partially replaced by fly ash or ground-granulated blast-furnace slag. Linear regression applied to verified UK cradle-to-gate data shows emissions fall almost proportionally with substitution, up to fifty percent. Replacing twenty percent of cement with fly ash lowers embodied carbon by roughly twelve percent within that range. A forty percent slag mix achieves about a twenty-seven percent reduction.

Strength data show fly ash is structurally reliable at fifteen to twenty percent replacement levels. Dosages above thirty per cent cause slower early-age strength development. Slag performs best at thirty and fifty percent and can slightly increase twenty-eight-day strength. Sensitivity analyses show the reported carbon savings are maintained only with moderate haulage distances, consideration of carbonation over service life, and careful assessment of high-loss-on-ignition fly ash.

These results inform a practical decision framework. Projects aiming for modest carbon reductions and accelerated schedules should utilize fly ash within the fifteen to twenty percent range. Greater reductions are achieved with approximately forty percent slag and supplementary design strategies. Given the limited global availability of these by-products, substitution should be combined with the adoption of emerging low-clinker binders, efficient structural designs, and comprehensive life-cycle reporting. Future research should incorporate region-specific transport inventories and dynamic allocation methodologies to more accurately assess the net benefits of low-carbon concrete in diverse markets.

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