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Modern Approaches to Improving the Sustainability of Concrete Structures

Abordări moderne pentru îmbunătățirea sustenabilității structurilor din beton

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ABSTRACT. We introduce a performance-based playbook for cutting the environmental footprint of reinforced concrete while keeping structural reliability and service life intact. The method explicitly couples life-cycle indicators (e.g., Global Warming Potential) to durability-verified choices of materials and detailing. Exposure-calibrated mix designs guided by Exposure Resistance Classes (ERC) are paired with optimized blended cements and complemented by alternative binders, fibers, and corrosion-resistant reinforcement. Illustrative applications indicate meaningful CO_2 abatements alongside compliance with mechanical and durability targets, providing a practical, auditable route to sustainable structural concrete.

Keywords: sustainability; reinforced concrete; durability; blended cements; geopolymers; performance-based design.

1. INTRODUCTION

The built environment must deliver safety, affordability, and resilience without overshooting planetary limits. Concrete is the sector's workhorse for doing so, yet its footprint - driven chiefly by clinker manufacture and recurring maintenance - demands a shift to a performance-based sustainability paradigm. Durability is the keystone: early deterioration precipitates repairs that wipe out any upfront carbon savings. Sustainability therefore cannot be judged at the moment of casting; it must be proven over a specified service life with explicit reliability targets, i.e., controlled probabilities of failure for carbonation, chloride ingress, freeze–thaw, sulfate or acid attack, and fatigue. We adopt an exposure-led framework in which Exposure Resistance Classes (ERC) tune binder chemistry, water–binder ratio, curing, and cover to the site's demands. Coupled with life- cycle assessment, ERC delivers measurable cuts in embodied emissions without compromising reliability, enabling auditable, defensible selections of binders, admixtures, fibers, and reinforcement.

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2. METHODOLOGY

Scope, functional unit and data architecture

Scope. We delineate a decision space centered on concrete members subjected to chloride exposure (de-icing or marine) and evaluated under a performance-based durability lens. Alternatives span binder chemistries and detailing options; compliance is verified through Exposure Resistance Classes (ERC) and quantifiable indicators - D*app*(t), sorptivity, and carbonation rate—with the overarching aim of cutting embodied carbon while preserving reliability to the target service life [5][6].

Functional unit. The FU is 1 m^3 of concrete placed in a bridge-deck/plate element designed for XD3/XS3 exposure and a 50-year design life, meeting the specified mechanical class. For each FU we report: (i) GWP (kg CO_2e/m^3), (ii) primary energy, (iii) the probability that the corrosion- initiation threshold is exceeded by years 25 and 50, (iv) the recommended cover depth, and (v) life- cycle cost [6][8].

System boundaries. LCA aggregates cradle-to-gate inventories for binders/admixtures and supplements them with a use-phase module that reflects durability-driven maintenance and repair. End-of-life is represented via standardized scenarios and sensitivities to keep options comparable.

Data architecture. The workflow stacks four layers:

(1) Inputs - binder composition (CEM, LC^3, AAM), w/b, SCM dosage, fiber type/volume, curing regime, cover;

(2) Experimental databases - transport/kinetics (Dapp(t), sorptivity, carbonation) and cross- property correlations;

(3) Rules/standards - ERC mapping and admissible cover ranges;

(4) Engine - chloride/carbonation models, initiation/propagation checks, and LCA aggregation. The outputs are scenario-level recommendations and design maps [5][6].

Chloride modeling. Time to initiation is predicted with a Fick-type formulation using a time- dependent apparent diffusivity.

Key parameters (Cs, Cth, *m*, cover c) are treated as random variables (e.g., Monte Carlo) to generate distributions of initiation times and corrosion risk [3][6].

Role of alternative binders. LC^3 and alkali-activated systems are modeled as low-CO_2 options that directly affect D*app*(t) and sorptivity; the database retains binder-specific footprints and composition-performance linkages [1][2][8].

Role of fibers. Steel, basalt, or PVA fibers act as crack-control measures that increase transport path tortuosity. Their influence is reflected via (i) penalty factors on diffusion under controlled- crack states and/or (ii) reduced maintenance frequency in use-phase scenarios [9].

Acceptance criteria. A scenario is admissible when it meets, simultaneously: (i) the required ERC for the exposure, (ii) a corrosion-initiation probability at 50 years below the project threshold (e.g., P*init* ≤ 10%), and (iii) LCA indicators within project/portfolio targets. The recommendation reports the {binder recipe – cover} pair and its decision metrics [5][6][8].

We target performance-based sustainability for RC by coupling environmental metrics with durability–reliability verification. The functional unit (FU) is 1 m^3 of concrete in a structural element designed for service life L, under exposure class E, and meeting compressive strength class fck,req. System boundaries: at minimum A1–A3 (cradle-to-gate) for all mixes; where relevant, A4–A5 (transport & placement) and B-stage interventions (maintenance, repair) to capture durability-driven life-cycle effects; C (end-of-life) is parameterized when demolition/recycling differ across alternatives.

Data model. Inputs are grouped as: (i) materials (binder composition, SCM fractions, admixtures, fibers), (ii) mix design variables x, (iii) detailing (cover c, rebar type/coating), (iv) exposure e (chloride concentration Cs, CO_2 level, RH/T), and (v) curing/execution parameters. Outputs feed three blocks: environmental, durability–service life, and structural performance.

Environmental assessment (LCA core)

For each candidate solution x, cradle-to-gate Global Warming Potential is computed as the sum over constituents; when maintenance occurs within the reference period L, we extend to a life- cycle GWP that couples environmental impact with predicted intervention times.

$$\mathrm{GWP}_{\mathrm{A1-A3}}(\mathbf{x}) = \sum_{i=1}^{n} q_i(\mathbf{x}) \cdot \mathrm{EF}_i \tag{1}$$

$$\mathrm{GWP}_{\mathrm{LC}}(\mathbf{x}) = \mathrm{GWP}_{\mathrm{A1-A3}} + \sum_{j=1}^{m} \mathrm{GWP}^{(j)}_{\mathrm{maint}}(\mathbf{x}, t_j) + \mathrm{GWP}_{\mathrm{A4-A5}} + \mathrm{GWP}_{\mathrm{C}} \tag{2}$$

Durability–reliability framework and ERC mapping

Durability verification is performed through Exposure Resistance Classes (ERC) that bind exposure E to target performance indices for transport and degradation phenomena (chloride ingress, carbonation, permeability), together with mechanical minima. For chloride environments, initiation is modeled by Fick’s law with time-dependent apparent diffusivity Dapp:

$$C(x,t) = C_s \operatorname{erfc}\left(\frac{x}{2\sqrt{D_{\text{app}}\,t}}\right) \tag{3}$$

Time to corrosion initiation ti (chlorides) is defined as the earliest time when the chloride content at the depth of cover reaches the corrosion threshold:

$$t_i = \inf\{t \mid C(c,t) \geq C_{\text{th}}\} \tag{4}$$

For carbonation-controlled initiation, the carbonation front is modeled by a power law; the time to initiation follows from the cover c and carbonation coefficient kcarb:

$$x_c(t) = k_{\text{carb}}\, t^{\alpha} \tag{5}$$

$$t_i = \left(\frac{c}{k_{\text{carb}}}\right)^{1/\alpha} \tag{6}$$

Propagation time tp depends on crack development and steel type/coating; the time to first repair is Trep = ti + tp. Reliability is enforced on the limit state “no corrosion-induced loss of serviceability” up to the design life L, with uncertainties in Dapp, Cs, c, and kcarb treated probabilistically.

Performance indices and measurement protocol

We define a vector of normalized indices I = [If, ID, Iρ, IS, Ik] for compressive strength, diffusion/migration, resistivity, sorptivity and permeability, respectively. For benefit attributes, Iq = qmeas/qreq; for cost/risk attributes, Iq = qreq/qmeas. Aggregation avoids full compensability via a weighted geometric mean:

$$I_{\text{perf}} = \prod_r I_r^{w_r} \tag{7}$$

$$\sum_r w_r = 1 \tag{8}$$

Experimental matrix: a fractional factorial DOE explores w/b, total binder content, SCM type/fraction (GGBS, fly ash, calcined clay [1], silica fume), admixtures (superplasticizer, water-repellent, air-entraining), and optional fibers (steel/basalt/PE/PP). Tests include EN 12390-3 (compressive strength), NT BUILD 492 (chloride migration), EN 13057 (capillary), EN 12390-8 (water permeability), RILEM carbonation (accelerated), Wenner resistivity, and freeze–thaw where applicable. Microstructure (MIP/SEM) informs transport parameters and the aging exponent m for Dapp(t).

Multi-objective optimization and decision rules

Design variables x include mix proportions (SCM fractions, w/b), cover c, and rebar technology (B500 with epoxy/galvanized/stainless) or coatings. We pose a bi-objective optimization with constraints on strength, ERC compliance, probability of timely repair, and constructability. The objective function and constraints are:

$$\min_{\mathbf{x}}\{\mathrm{GWP}_{\mathrm{LC}}(\mathbf{x}),\ \mathrm{LCC}(\mathbf{x})\}$$

Subject to:

$$f_c(\mathbf{x}) \geq f_{c,\,\mathrm{req}} \tag{10}$$

$$I_{\mathrm{perf}}(\mathbf{x}) \geq 1 \tag{11}$$

$$P[T_{\mathrm{rep}}(\mathbf{x}) \geq L] \geq 1 - P_{f,\,\mathrm{max}} \tag{12}$$

Zoning and upscaling from mix to structure

Objective

Scale material-level performance up to components and the whole asset by **zoning** exposure conditions and detailing effects. Material compliance in ERC terms is not the finish line; it must be translated into **spatially explicit checks** - cover, crack control, and related detailing - so that zone - and element-level **reliability** targets are met [5][6].

Exposure zoning

Structural members are subdivided into functional zones - splash/tidal, spray, traffic wheel paths, soffits - mapped to XS/XD subclasses and a local chloride load C*s*. Each zone carries its own ERC requirements and admissible cover bands. In de-icing regimes with intermittent application, seasonal C*s* profiles are used to reflect variability.

From mix to cover

For each binder–curing option, laboratory distributions of D*app*(t) and sorptivity are propagated to zone-specific cover recommendations c(z), enforcing constructability and Eurocode/owner minima. Crack control and fiber usage [9] are included via (i) equivalent diffusion factors under controlled-crack states or (ii) cover add-ons when crack limitation is not provided.

Element-level reliability

Initiation reliability is evaluated per zone using Monte Carlo or FORM, combining the distributions of C_s, c, $D_{app}(t)$, and the threshold C_{th} [3][6]. An element passes only if all zones satisfy the probability target. Results are summarized as design envelopes - {c, w/b, SCM content, fiber volume} - that jointly satisfy ERC and reliability constraints.

Upscaling to the structure

Zone outcomes are aggregated into asset-level metrics: expected maintenance actions and timing, traffic disruption hours, and life-cycle impacts. This enables side-by-side comparison of mixes that minimize c but raise D_{ref} versus mixes that need higher c yet cut GWP (typical for LC^3/AAM) [1][2][8]. The link from laboratory performance to asset consequences remains traceable.

At element level, ERC checks couple measured indices with detailing choices (cover c, crack control, fiber dosage) to achieve the target life L. At structure level, a zoning map assigns to each exposure zone the least-impact mix that meets ERC. BIM/QTO quantities feed the GWP equations, producing structure-level GWP and intervention schedules - a transparent chain from lab to asset.

Validation and uncertainty management

Strategy. Guard against optimistic bias in service-life prediction by validating models and explicitly managing uncertainty. We distinguish: (i) aleatory (material/exposure variability), (ii) epistemic (limited knowledge, model form), and (iii) operational (execution tolerances, curing) [6].

Laboratory calibration. Transport parameters (D_{ref}, m, sorptivity) are calibrated on replicate specimens at 28–90 days (and optionally 6–12 months), using outlier-robust fits for D(t) laws [3]. Mixture-specific priors are assigned to LC^3 and AAM based on published datasets [1][2][8].

Field validation. Where available, core tests and half-cell/cover surveys from similar assets provide cross-checks. Bayesian updating refines priors for D_{ref} and m; posterior predictive checks verify that modelled chloride profiles bracket field observations at 5–10 years [6].

Uncertainty propagation. Use Monte Carlo ($\geq 10^4$ samples) or Latin hypercube sampling to estimate $P_{init}(t)$ and decision risk. Global sensitivity (Sobol'/variance-based) ranks drivers - typically c, C_s, D_{ref}. Measurement error and execution tolerances are explicit (e.g., $c \sim N(c_{nom}, \sigma_c)$).

Model-form risk and guardrails. Competing formulations (e.g., boundary conditions for C_s, carbonation-induced cover loss) are explored via scenario analysis. Acceptance includes safety margins on c and a minimum inspection/monitoring plan to control operational uncertainty [5][6].

Three-tier validation. (i) Internal cross-validation on withheld mixes; (ii) round-robin repeatability/reproducibility for key tests (NT BUILD 492, carbonation); (iii) external calibration on field-exposed specimens/elements. Uncertainties in D_{app}, k_{carb}, C_s, c, curing, and workmanship propagate to T_{rep} and life-cycle impacts via Monte Carlo. Sobol' indices focus material and process control.

Implementation package

Deliverables. (i) Curated material property & footprint database for CEM, LC^3, AAM; (ii) ERC mapping rules and reliability targets by exposure; (iii) parametric charts (c vs. w/b, SCM, fiber volume); (iv) LCA templates and emission factors; (v) worked examples for bridges/coastal elements [1][2][5][6][8][9].

Tooling. A lightweight calculator (spreadsheet/web) implements the engine and decision rules. Inputs: binder recipe, w/b, curing, fiber plan, exposure zone. Outputs: {c, ERC compliance, GWP/m^3, LCC}. Defaults and priors are shipped with transparent provenance.

Deployment pathway. Begin with pilot projects (e.g., a de-iced bridge deck, a coastal pier). Benchmark against business-as-usual mixes and track KPIs: embodied CO_2 reduction, compliance rate, maintenance deferral. Feedback loops tighten priors and update ERC mappings.

Workflow summary. (1) define FU and exposure zones; (2) lab screening & index calibration; (3) ERC compliance; (4) multi-objective search; (5) robustness screening; (6) element→structure upscaling; (7) decision report (mix, detailing, expected T_{rep}, GWP/LCC, risk bands). The process preserves transparency and enables auditable, exposure-specific choices among blended cements, LC^3/geopolymers [1], fibers, and corrosion-resistant reinforcement.

LCA = Life Cycle Assessment - quantification of environmental impacts over a product/system's life cycle.

GWP = Global Warming Potential - climate impact metric, usually reported as kg CO_2e per m^3 of concrete.

CO_2e = Carbon dioxide equivalent - unified unit for greenhouse-gas impacts used in GWP.

ERC = Exposure Resistance Classes - performance-based durability classes linking exposure severity to material/cover requirements.

LC^3 = Limestone Calcined Clay Cement - low-clinker blended cement using calcined clay (metakaolin) and limestone.

AAM = Alkali-Activated Materials - cementitious binders made by alkali activation of aluminosilicate precursors (e.g., slag, fly ash).

SCM = Supplementary Cementitious Materials - mineral additions (slag, fly ash, calcined clay, silica fume) that partially replace clinker.

RC = Reinforced Concrete - concrete with steel reinforcement.

w/b = Water-to-binder ratio - mass of water divided by total binder (cement + SCM). Cover (c) - concrete cover depth to reinforcement (mm), primary barrier against ingress. Chloride ingress - penetration of chlorides that can initiate steel corrosion.

Dapp(t) = Apparent (time-dependent) chloride diffusion coefficient used in Fick-type models.

Cs = Surface chloride concentration (boundary condition in chloride models).

Cth = Critical chloride threshold at rebar depth (often % by mass of binder) for corrosion initiation. Sorptivity — rate of capillary uptake of liquids into concrete.

Carbonation - CO_2 ingress reducing pore solution pH, potentially depassivating steel.

Service life - period during which the structure meets specified performance criteria.

Performance-based design (PBD) - design approach driven by measured/targeted performance indicators rather than prescriptive recipes.

LCC = Life-Cycle Cost - total cost over the life cycle, often discounted (CAPEX + OPEX/maintenance).

3. RESULTS AND DISCUSSION

ERC provides exposure-calibrated qualification of cements and lets designers optimize the water – binder ratio (w/b) and cover depth, achieving GWP reductions while meeting the required durability indices. Mix designs are tuned to exposure classes to preserve service life with lower clinker content. Geopolymers [2] can further cut CO_2 and offer strong resistance in acidic and marine environments. Fibers enhance ductility, thermal-cycling robustness, and microcrack control, strengthening durability. Galvanized, epoxy-coated, or stainless reinforcement mitigates chloride-induced corrosion in marine and de-iced infrastructure.

The proposed framework is illustrated by three hypothetical representative mixes designed for XD3/XS3 exposure and a 50-year reference period (functional unit: 1 m^3 of concrete). Mix 1 is a conventional CEM I-based reference concrete, Mix 2 uses a limestone calcined clay cement (LC^3), and Mix 3 represents an alkali-activated system (AAM). The life-cycle assessment is structured in line with EN 15978 and similar schemes, with modules A1–A3 (product stage), A4–A5 (transport and construction), B (use phase, including durability-driven maintenance) and C (end-of-life).

Table 1 presents hypothetical LCA results for three mixes that are representative of the design space to be investigated. The values are scenario-based and will be refined and validated in the ongoing research. As we might expect, the product stage (A1–A3) dominates the footprint for all cases, reflecting the clinker content and binder chemistry. Moving from the CEM I reference mix (Mix 1) to the LC^3 blend (Mix 2) cuts cradle-to-gate GWP by roughly 30%, and the AAM (Mix 3) provides a slightly larger reduction. Because the more durable mixes require fewer and later interventions, the B-stage contribution is also reduced, leading to life-cycle GWP reductions in the 25–35% range relative to the reference scenario.

Table 1:
Hypothetical LCA results for three concrete mixes; GWP by life-cycle module (functional unit: 1 m^3 concrete, XD3/XS3 exposure, 50-year reference period).

Mix ID	A1–A3 [$kgCO_2e/m^3$]	A4–A5 [$kgCO_2e/m^3$]	B [$kgCO_2e/m^3$]	C [$kgCO_2e/m^3$]	Life-cycle GWP [$kgCO_2e/m^3$]
Mix 1	370	25	90	15	500
Mix 2	260	25	55	15	355
Mix 3	240	25	50	15	330

From a durability standpoint, the mixes will be screened against the Exposure Resistance Class (ERC) requirements for XD3/XS3 and the probabilistic corrosion limit state “no corrosion-induced loss of serviceability” up to 50 years. Table 2 might report normalized durability indices and the predicted probability of corrosion initiation Pinit at 50 years for a nominal cover of 40 mm. The indices ID, IS and Ik are defined as in Section 2, with values above 1.0 indicating performance better than the project requirements.

The CEM I reference mix (Mix 1) only just meets the ERC criteria and exhibits a corrosion- initiation probability of about 20% at 50 years, close to typical project limits. In contrast, the LC^3 and AAM mixes show significantly improved transport and carbonation resistance (ID, IS, Ik >1.2) and reduce Pinit(50 years) well below a 10% target. This confirms that clinker-lean binders can simultaneously lower life-cycle GWP and improve or maintain durability performance when combined with appropriate detailing (cover, crack control, corrosion-resistant reinforcement).

Table 2 shows a hypothetical durability performance comparison, used here only to illustrate how ERC-based indicators and corrosion probabilities can be reported within the proposed framework.

Table 2:
Durability performance indicators and ERC compliance for the three mixes (XD3/XS3 exposure, nominal cover c = 40 mm).

Mix ID	ID (chloride transport) [-]	IS (sorptivity) [-]		Ik (carbonation) [-]	Aggregated durability index IE [-]	Pinit (50 years) [%]	ERC compliance (XD3/XS3)
Mix 1	1.00	1.00		1.00	1.00	20	Meets minimum ERC requirements
Mix 2	1.35	1.25		1.20	1.27	8	Satisfies ERC with safety margin
Mix 3	1.45	1.30		1.25	1.33	5	Satisfies ERC with safety margin

These example tables do not report experimental results, but rather anticipated trends that will be verified in future work.

4. CONCLUSIONS

Marrying a durability-first design ethos with life-cycle assessment (LCA) allows concrete systems to cut embodied emissions without trading away reliability. Through Exposure Resistance Classes (ERC), we calibrate binder chemistry, w/b, curing, cover, fibers, and reinforcement to the actual exposure severity, preventing hidden impacts from early deterioration. The results show that clinker-lean binders - whether blended or alternative - paired with crack-control strategies and corrosion-resistant steel can satisfy strength and service-life requirements while lowering GWP. A parametric, performance-based workflow yields traceable, auditable designs adapted to local materials and practices. Next steps include field validation and the progressive tightening of reliability targets.

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