

Integrated Low-Carbon, Self-Healing, and Sensor-Enabled Concrete: A Multi-Objective Framework for Next-Generation Civil Infrastructure

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Abstract—Concrete innovation is often evaluated as a collection of isolated technologies: a low-clinker binder, a self-healing agent, a conductive filler, or a robotic deposition process. This paper develops an integrated design framework in which these functions are selected together against strength, durability, carbon, cost, constructability, and monitoring requirements. The proposed platform combines limestone-calcined clay cement (LC3), limited biochar and recycled-mineral fractions, moisture-activated mineral or microbial healing, and a percolating carbon-based sensing network. A structured evidence review is coupled with a transparent computational scenario study. Six candidate mixtures are compared using mass-balance embodied-carbon calculations, crack-closure kinetics, resistive sensing relationships, service-life logic, and multi-objective ranking. The scenario analysis indicates that a fully integrated candidate can lower cradle-to-gate global-warming potential by approximately 38–47% relative to the reference mixture while preserving a 28-day compressive-strength class suitable for common structural applications. Healing functionality is most valuable when it delays transport-controlled corrosion rather than when surface closure alone is treated as success. Sensing functionality is shown to require moisture and temperature compensation, four-probe measurement, and calibration after cracking and healing. The paper contributes: (i) a systems architecture for multifunctional concrete; (ii) equations and decision variables suitable for optimization; (iii) a staged verification protocol spanning fresh properties, mechanical response, transport, healing, sensing, and life-cycle assessment; and (iv) an implementation roadmap for Indian infrastructure. All numerical results in the scenario section are illustrative model outputs, not claimed laboratory measurements. The framework is intended to guide subsequent experimental validation and field demonstration.

Index Terms—LC3, low-carbon concrete, self-healing concrete, bacterial concrete, biochar, self-sensing concrete, 3-D concrete printing, recycled aggregate, life-cycle assessment, multi-objective optimization.

I. INTRODUCTION

CONCRETE underpins buildings, bridges, water systems, transport corridors, and energy infrastructure, but its familiar composition hides a difficult optimization problem. Structural strength alone is no longer an adequate design target. Modern mixtures must limit clinker-related emissions, tolerate variable supplementary cementitious materials, resist aggressive exposure, close or seal service cracks, communicate damage before failure, and remain placeable through conventional or automated construction. These functions interact. A conductive addition can reduce workability; an encapsulated healing carrier can increase porosity; a low-clinker binder can alter early-age strength and the chemical environment needed for mineral healing; and printing requirements can conflict with pumpability or interlayer bond. Treating each innovation independently can therefore produce a technically impressive ingredient but an unbalanced concrete system.

The decarbonization need is immediate. Cement process emissions arise primarily from limestone calcination, while kiln fuel, electricity, transport, and construction losses add further burdens. Industry roadmaps consequently emphasize clinker substitution, material efficiency, alternative fuels, carbon capture, and performance-based specifications [1]–[4]. LC3 is attractive because a typical blend uses about 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum; the coupled alumina–carbonate chemistry can sustain useful strength while substantially reducing clinker demand [5]–[8]. Carbonation curing, recycled mineral fractions, and responsibly produced biochar offer additional but boundary-sensitive reductions [9]–[12].

Durability is the second lever. A lower cradle-to-gate footprint is not automatically a lower life-cycle footprint if premature cracking increases repair frequency. Concrete is quasi-brittle, and cracks create preferential pathways for chlorides, carbon dioxide, sulfates, and water. Autonomous healing technologies seek to seal these paths through continued hydration, carbonation, expansive minerals, polymeric agents, vascular delivery, or microbially induced carbonate precipitation [13]–[18]. The most meaningful performance metric is not a photograph of surface closure; it is recovery of transport resistance, stiffness, corrosion protection, or another function linked to the structure's exposure and limit state.

The third lever is information. Distributed sensing ordinarily requires attached or embedded devices whose durability and representativeness may be uncertain. Carbon fibers, carbon black, graphene-related fillers, steel fibers, and conductive admixtures can form a piezoresistive network within the cement matrix, allowing changes in electrical resistance to indicate strain or damage [19]–[22]. When combined with digital twins and data-driven mixture design, the concrete becomes both material and measurement layer. Yet the electrical response is also sensitive to moisture, temperature, ionic conduction, electrode contact, and loading history; without compensation, apparent damage may be environmental drift.



Fig. 1. Proposed integrated architecture linking material functions, digital design, and manufacturing.

This paper addresses the integration gap. It is a critical synthesis and computational design study rather than a report of completed laboratory experiments. The central hypothesis is that a medium-strength LC3 matrix can act as a stable host for localized healing reservoirs and a low-volume conductive network, provided that dispersion, rheology, curing, and durability are treated as coupled constraints. The framework compares six transparent scenarios and identifies a staged test programme that can convert the concept into verifiable engineering evidence. The main novelty lies in system-level co-design: carbon reduction, crack management, sensing, and construction are optimized together rather than appended sequentially.

II. INNOVATION LANDSCAPE AND RESEARCH GAP

A. Low-Clinker Binder Systems

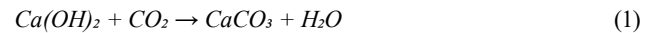
The practical climate advantage of LC3 follows from reducing the clinker fraction while using widely available kaolinitic clays and limestone. Calcination of clay occurs at a lower temperature than clinker formation and does not include limestone-process emissions of the same magnitude. In the hydrated binder, metakaolin supplies reactive alumina and silica; limestone participates in carboaluminate formation; and the combined system can refine the pore structure. The precise response depends on kaolinite content, fineness, sulfate balance, water demand, curing temperature, and compatibility with polycarboxylate-based admixtures. Accordingly, LC3 should be specified through performance tests and characterized feedstocks rather than only a nominal replacement percentage [5]–[8].

Other low-carbon binders—high-volume slag or fly-ash blends, alkali-activated materials, belite-rich clinker, calcium sulfoaluminate systems, and calcined-clay variants—remain important. Their selection is regional. Fly ash quality and availability may decline as coal power changes; slag is valuable but geographically constrained; alkali-activated systems may face activator impacts and unfamiliar standards. A robust innovation platform therefore uses local material inventories and allows the binder module to change while retaining common durability, sensing, and healing verification.

B. Carbon Mineralization and Biochar

Accelerated carbonation curing exposes early-age precast material or recycled concrete fines to controlled carbon dioxide. The gas dissolves in pore water and reacts with calcium-bearing phases to form stable carbonates. Under suitable moisture, pressure, and timing, the process can densify the near-surface region and contribute early strength [9], [10]. However, uptake must be measured by mass balance or thermogravimetric methods, and any delivered

CO₂, compression energy, leakage, and curing infrastructure must be included in the inventory. Natural carbonation over a structure's life is real but uncertain and should not be credited in a cradle-to-gate declaration unless the declared boundary and method explicitly allow it [11].



Biochar provides a different route: biogenic carbon may remain stored in a porous, carbon-rich solid made by pyrolysis. Small additions can act as internal-curing reservoirs or nucleation surfaces, but excessive dosage may increase water demand, entrain voids, or reduce strength. The net benefit depends on biomass source, counterfactual fate, pyrolysis energy, transport, permanence, and allocation of co-products. Therefore, “carbon-negative concrete” is not an intrinsic material label; it is a quantified claim tied to a functional unit, baseline, system boundary, and verified inventory [12].

C. Autonomous Crack Management

Self-healing mechanisms can be organized by activation and delivery. Autogenous healing consumes remaining binder and precipitates carbonates in small cracks. Crystalline admixtures promote insoluble products when water enters. Capsules rupture under crack opening and release polymeric or mineral precursors. Vascular networks can replenish agents but complicate construction. Microbial routes protect dormant alkaliphilic spores and nutrients in lightweight aggregates, hydrogel, diatomaceous earth, expanded perlite, or engineered capsules; water ingress activates metabolism or urease-mediated pathways and carbonate precipitates in the crack [13]–[18].



Fig. 2. Conceptual moisture-triggered bio-mineral healing mechanism within a cracked cementitious matrix.

Crack width, connectivity, water availability, temperature, repeated opening, nutrient accessibility, and bacterial viability govern performance. Small cracks may close rapidly, whereas wider or moving cracks require fiber bridging, multiple reservoirs, or external intervention. Ureolytic systems can generate ammonium and require environmental control; non-ureolytic pathways may reduce this concern but can heal more slowly. A credible design must therefore state the biological strain or mineral route, carrier, dosage, activation condition, target crack-width class, shelf life, and biosafety considerations.

D. Self-Sensing Cementitious Composites

Piezoresistive concrete relies on a conductive network close to its percolation threshold. Under compression or tension, contact distance, tunneling resistance, and microcrack geometry change, producing a measurable fractional resistance change. A common sensitivity measure is the gauge factor:

$$GF = (\Delta R/R_0)/\epsilon \quad (2)$$

where R_0 is baseline resistance, ΔR is the resistance change, and ϵ is mechanical strain. A four-probe arrangement

separates current injection from voltage measurement and reduces the influence of electrode contact. Alternating-current impedance can further distinguish bulk, interfacial, and polarization effects. Uniform dispersion is essential: agglomerated nanocarbon increases variability and may harm rheology, while too much conductive filler reduces sensitivity because the network becomes insensitive to small contact changes [19]–[22].

E. Additive Construction and AI-Assisted Design

Extrusion-based 3-D concrete printing removes formwork and enables topology-aware material placement, but it imposes a narrow fresh-state window. The material must pump without blockage, extrude with dimensional stability, bond between layers, and build vertically without collapse. Print-path pauses create anisotropic interfaces; reinforcement integration, curing, quality assurance, and acceptance criteria remain active standardization topics [23]–[25]. The integrated concrete proposed here is not assumed printable by default. A printable variant requires separate rheological qualification and interlayer durability testing.

Data-driven models can predict strength, slump, carbon, or cost from mixture variables and can search a multi-objective design space [26], [27]. Their utility depends on data provenance, feature coverage, measurement consistency, and uncertainty. Models trained on ordinary Portland cement mixtures may extrapolate poorly to LC3, capsules, biochar, or conductive fillers. Physics-informed constraints, uncertainty penalties, and targeted experiments are therefore preferable to an unconstrained black-box optimum.

TABLE I
FUNCTIONAL MAP OF THE INNOVATION MODULES

Innovation	Primary function	Main benefit	Critical constraint
LC3	Clinker reduction	Lower GWP; scalable feedstocks	Clay reactivity, sulfate balance
CO ₂ curing	Mineral storage	Early densification; measured uptake	Precast access; boundary accounting
Biochar	Biogenic C storage	Internal curing; carbon retention	Water demand; source permanence
Bio/mineral healing	Crack sealing	Lower ingress and repair demand	Activation, crack width, repeatability
Conductive network	Strain/damage sensing	Distributed structural information	Dispersion and environmental drift
3-D printing	Formless placement	Geometry and material efficiency	Buildability and interlayer bond
AI optimization	Design-space search	Balances competing objectives	Dataset shift and uncertainty

F. Research Gap

Published studies typically optimize one axis: clinker reduction, crack closure, electrical sensitivity, or printability. Few frameworks define how these modules compete for water, volume, admixture demand, curing, and cost. Fewer still connect healing to a service-life metric or sensing to a calibration and data-governance plan. The research gap is therefore not another isolated additive; it is an auditable systems method that identifies feasible combinations, rejects incompatible ones early, and supports progressive evidence from paste to field element.

III. PROPOSED MULTI-OBJECTIVE DESIGN FRAMEWORK

A. Functional Unit and Boundary

The reference functional unit is 1 m³ of structural concrete delivered at the plant gate, achieving at least 45 MPa 28-day compressive strength, a specified workability class, and a 50-year nominal reference life. For whole-life comparison, the unit is extended to 1 m³ of concrete performing the same structural and exposure function over 100 years. The cradle-to-gate inventory includes raw-material production, processing, and inbound transport. Optional modules add carbonation curing, placement energy, repair materials, traffic disruption, demolition, and recycling. Results must never mix these boundaries without a clearly labeled scenario.

$$GWP_{mix} = \sum(m_i \cdot EF_i) + E_{mix} \cdot EF_e - mCO_{2,stored} \quad (3)$$

In (3), m_i is the mass of constituent i , EF_i is its region-specific emission factor, E_{mix} is processing energy, EF_e is the energy factor, and $mCO_{2,stored}$ is verified mineralized or permanently stored carbon. Avoided future repair is not subtracted here; it enters the whole-life model with an explicit probability and timing.

B. Decision Variables and Constraints

The principal mixture variables are total binder B , water-to-binder ratio w/B , clinker fraction f_{cl} , calcined-clay and limestone fractions, biochar dosage f_{bc} , recycled coarse and fine aggregate fractions, healing-carrier volume f_h , conductive-filler dosage f_c , fiber volume, admixture dosage, and curing protocol. Process variables include mixer energy, dispersion sequence, CO₂ exposure, nozzle geometry, layer time, and electrode spacing. Design variables are bounded by material availability and testable constraints rather than arbitrary numerical ranges.

$$x = [B, w/B, f_{cl}, f_{cc}, f_{ls}, f_{bc}, f_h, f_c, V_f, t_{cure}]^T \quad (4)$$

Feasibility constraints include minimum characteristic strength, slump or print-window limits, maximum shrinkage, minimum transport resistance, capsule survivability, electrical resistivity within the acquisition range, and cost or carbon caps. For a printable mixture, pumpability, extrudability, buildability, open time, layer geometry, and interlayer bond are additional constraints. Constraints should be evaluated probabilistically when inputs are variable.

C. Objective Functions

A scalar score is convenient for ranking but can conceal value judgments. The preferred output is a Pareto set that exposes trade-offs among global-warming potential G , cost C , strength margin S , transport index D , healing H , sensing robustness Q , and constructability P . A normalized decision score may be used only after stakeholder weights are disclosed:

$$J(x) = w_G \cdot \hat{G} + w_C \cdot \hat{C} - w_S \cdot \hat{S} - w_D \cdot \hat{D} - w_H \cdot \hat{H} - w_Q \cdot \hat{Q} - w_P \cdot \hat{P} \quad (5)$$

Lower J is preferred when beneficial quantities are expressed with negative signs. Weights should be tested in sensitivity analysis, not presented as universal. A public bridge deck may assign high weights to chloride resistance, monitoring, and repair disruption; a low-rise precast wall may emphasize carbon, early strength, repeatability, and cost; a temporary printed component may prioritize geometry and material efficiency.

D. Healing and Sensing Submodels

For screening, crack closure can be represented by a bounded first-order response dependent on crack width w_0 , moisture availability M , healing-agent reserve A , and

temperature factor θ . The expression is phenomenological and must be recalibrated from image-based closure and permeability recovery data:

$$H(t) = H_{\max}(w_0, M, A, \theta) [1 - \exp(-kh \cdot t)] \quad (6)$$

Electrical response is decomposed into mechanical, thermal, moisture, and irreversible damage components. This prevents environmental changes from being mistaken for strain:

$$\Delta R/R_0 = GF \cdot \varepsilon + \alpha T \Delta T + \alpha M \Delta M + D_{cr} + \eta \quad (7)$$

Here αT and αM are calibration coefficients, D_{cr} represents persistent crack-related change, and η includes noise and electrode uncertainty. Multivariate compensation can be implemented in a digital twin, but the raw channels, preprocessing, calibration intervals, and uncertainty must remain auditable.

E. Service-Life Logic

For chloride exposure, a simplified diffusion-based initiation model can screen the effect of transport resistance and crack healing. The apparent diffusion coefficient D_{app} is reduced after successful sealing but allowed to recover if cracks reopen. A probabilistic limit state compares chloride concentration at reinforcement depth with a threshold value. Service life is the sum of initiation and propagation periods, with maintenance events represented as conditional branches rather than guaranteed benefits.

$$C(x, t) = C_s [1 - \operatorname{erf}(x / (2\sqrt{(D_{app} \cdot t))})] \quad (8)$$

Equation (8) is a screening model, not a substitute for exposure-specific calibration. Binding, aging, wetting-drying, temperature, convection, and cracks may dominate. Nonetheless, it makes the design logic explicit: healing has value when it reduces effective transport sufficiently and for long enough to defer corrosion or leakage.

Evidence ladder from laboratory formulation to auditable field deployment

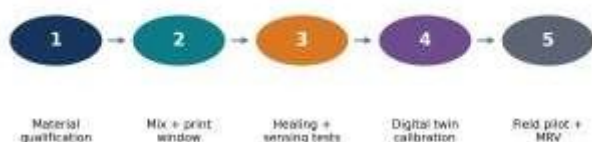


Fig. 3. Staged evidence ladder for development and deployment of the integrated concrete.

IV. MATERIALS ARCHITECTURE AND CANDIDATE MIXES

A. Reference Constituents

The proposed baseline uses locally available Portland clinker or general-purpose cement, calcined clay characterized for kaolinite content and reactivity, limestone of controlled fineness, gypsum adjusted for sulfate balance, potable or quality-controlled recycled water, well-graded aggregates, and a compatible high-range water reducer. A low-volume biochar option is pre-saturated or moisture-conditioned to reduce uncontrolled water absorption. Recycled aggregate is processed to limit attached mortar variability, contaminants, and excessive absorption. All moisture corrections are recorded batch by batch.

The healing module may use encapsulated non-pathogenic spores with a calcium-bearing nutrient, or an inorganic

crystalline/mineral precursor when biosafety, storage, or temperature makes a biological route unsuitable. The sensing module uses carbon black, short carbon fibers, or a hybrid network selected by dispersion trials. Conductive filler is not dosed solely by mass; the percolation response, workability, air content, and electrode geometry are evaluated together.

TABLE II
CANDIDATE MIXTURE ARCHITECTURES

ID	Binder / additions	Healing	Sensing	Intended route
C0	OPC reference	None	None	Conventional cast
C1	LC3-50	Autogenous	None	Cast / precast
C2	LC3 + 1% biochar	Autogenous	None	Precast
C3	LC3 + carrier	Bio/mineral	None	Durable cast
C4	LC3 + carrier	Bio/mineral	Carbon hybrid	Smart structural
C5	LC3 + recycled fines	Bio/mineral	Carbon hybrid	Printable variant

B. Mixing Sequence

A reproducible sequence is essential because multifunctional additions are sensitive to shear and timing. Dry aggregate and binder are premixed; preconditioned biochar and recycled aggregate moisture are included in the effective-water calculation. Conductive fillers are dispersed in a measured portion of mixing water with compatible surfactant or superplasticizer and controlled energy. Remaining water and admixture are added gradually. Fragile healing capsules are introduced late at low shear. For bacterial carriers, temperature and mixing time are limited to protect viability. A sample is retained for fresh-state electrical and microscopy checks.

The sequence should include a dispersion acceptance criterion. Candidate metrics include coefficient of variation of electrical resistivity across replicate prisms, optical or electron microscopy of agglomerates, and rheological hysteresis. A mixture that meets compressive strength but fails dispersion uniformity is not a sensing concrete; it is a heterogeneous conductive composite with unreliable output.

C. Volumetric and Water Corrections

All mixtures are proportioned by absolute volume. Absorbed water in recycled aggregate and biochar is distinguished from free water. Carrier and capsule volumes replace mortar volume rather than being added without compensation. Entrapped and entrained air are measured, because a small change in air can explain apparent losses attributed to an innovative additive. The mass balance is:

$$\Sigma(mi/\rho_i) + V_{air} = 1.000 \text{ m}^3 \quad (9)$$

V. EXPERIMENTAL VALIDATION PROGRAMME

A. Phase 1—Constituent Screening

Phase 1 characterizes chemistry, mineralogy, particle-size distribution, specific surface, density, water absorption, and thermal stability. Calcined clay is screened for reactivity and sulfate demand. Biochar is assessed for carbon content, ash, pH, leachable contaminants, pore structure, moisture sorption, and stability. Healing carriers are tested for crushing resistance, survival during mixing, storage life, and release under controlled cracking. Conductive dispersions are examined for sedimentation and percolation behavior.

B. Phase 2—Fresh and Early-Age Performance

Conventional mixtures are tested for slump or flow, air content, density, temperature, setting, segregation, and pumpability where relevant. Printable mixtures require rotational or vane rheometry, static-yield-stress rebuilding, extrusion pressure, filament geometry, layer deformation, open time, and buildability. Early-age calorimetry identifies retardation from biochar, nutrients, dispersants, or high admixture dosage. Autogenous shrinkage, plastic shrinkage, and temperature rise are measured because early cracking can overwhelm later healing capacity.

C. Phase 3—Mechanical and Transport Tests

Mechanical tests include compressive strength at 1, 7, 28, 56, and 90 days; splitting tensile or flexural strength; elastic modulus; and fracture or residual performance when fibers are used. Durability indicators include water absorption, sorptivity, electrical resistivity, rapid chloride migration or diffusion, chloride profiling, carbonation depth, sulfate exposure, freeze-thaw response where relevant, and restrained shrinkage. For printed specimens, tests are oriented parallel, perpendicular, and inclined to layers to quantify anisotropy.

D. Phase 4—Controlled Cracking and Healing

Specimens are precracked at a defined age using splitting, flexural, or wedge-splitting control. Crack widths are measured at multiple locations and grouped, for example, into 0.10–0.20, 0.20–0.35, 0.35–0.50, and 0.50–0.80 mm classes. Conditioning regimes include continuous water, wet-dry cycling, high humidity, and exposure-specific solutions. Surface closure is quantified from registered images, while functional recovery is measured by water permeability, sorptivity, chloride migration, ultrasonic pulse velocity, resonance, or stiffness recovery. Recracking tests establish whether healing is repeatable or a one-time event.

$$\eta_{\text{seal}} = [1 - q_{\text{healed}}/q_{\text{cracked}}] \times 100\% \quad (10)$$

In (10), q is flow or permeability under a consistent hydraulic boundary. A specimen with 95% surface closure but only 30% sealing efficiency should not be classified as fully healed. Mineral identity is confirmed by microscopy, spectroscopy, diffraction, or thermal analysis where feasible. For microbial systems, viability and environmental release are assessed using appropriate biosafety protocols.

E. Phase 5—Sensing Validation

Four-probe electrodes are cast or printed with defined spacing and corrosion-resistant contacts. Baseline impedance is recorded across frequency, moisture state, and temperature. Cyclic compression and flexure assess linearity, hysteresis, repeatability, drift, and fatigue response. Crack formation and subsequent healing are monitored to determine whether resistance returns, stabilizes at a new baseline, or remains permanently shifted. Separate temperature and humidity sensors provide compensation variables. Blind load cases are used to evaluate prediction error rather than reporting only fitted calibration data.

TABLE III
MINIMUM VALIDATION MATRIX

Domain	Minimum metric	Acceptance concept
Fresh state	Slump/flow, air, density	Within project placement window
Mechanical	f'_c , f_t , E , residual response	Meets structural class with margin
Transport	Sorptivity, resistivity, chloride	No penalty vs. durable control
Healing	Closure + permeability recovery	Target crack class and exposure

Domain	Minimum metric	Acceptance concept
Sensing	GF, hysteresis, drift, RMSE	Stable after compensation
Printing	Extrusion, buildability, bond	Validated anisotropic properties
LCA	GWP with uncertainty	Same function and boundary

F. Statistics and Reproducibility

Randomization, blinded image analysis, and power-based replicate counts are recommended. At least three independent batches should be separated from within-batch replicates. Report mean, standard deviation, confidence intervals, effect sizes, and all exclusions. Factorial or response-surface designs can screen interactions among clinker fraction, healing carrier, conductive filler, and curing. Model selection should use nested cross-validation or an external test set, and all preprocessing must be fitted only on training data. Raw measurements, mixture metadata, and analysis code should be archived with stable identifiers.

VI. COMPUTATIONAL SCENARIO STUDY

A. Scope and Assumptions

The following analysis is intentionally illustrative. It demonstrates the framework using six internally consistent scenarios; it does not represent tests performed by the author. Strength, carbon, cost, healing, sensing, and service-life inputs are plausible screening values synthesized from reported ranges and engineering judgment. They must be replaced by regional environmental product declarations, supplier data, and laboratory measurements before design or publication as experimental evidence.

TABLE IV
ILLUSTRATIVE SCENARIO INPUTS AND OUTPUTS

Scenario	f'_c (MPa)	GWP (kg CO ₂ e/m ³)	Relative cost	Closure (%)	Life (yr)
C0	55	390	1.00	12	50
C1	53	250	0.96	18	55
C2	51	215	1.01	25	58
C3	50	235	1.18	75	82
C4	49	242	1.25	73	88
C5	46	205	1.30	70	78

B. Embodied Carbon

Clinker substitution dominates the cradle-to-gate reduction. Scenario C1 lowers the illustrative GWP from 390 to 250 kg CO₂e/m³, while C2 reaches 215 kg CO₂e/m³ after limited biochar credit and adjusted processing. Healing carriers and conductive fillers add burden in C3 and C4, but their total remains below the reference because the LC3 matrix carries the main reduction. C5 combines low-clinker binder, recycled fines, targeted material placement, and a conservative storage credit to reach 205 kg CO₂e/m³. This apparent 47% reduction is a scenario result, not a universal product factor.

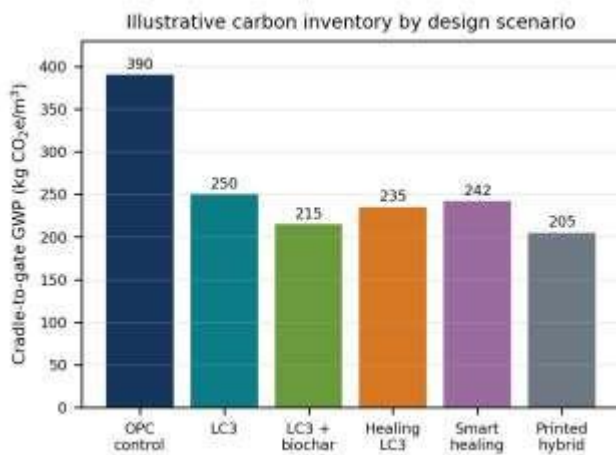


Fig. 4. Illustrative cradle-to-gate global-warming potential of candidate mixtures.

The carbon hierarchy is informative. First reduce avoidable binder and clinker; then optimize aggregate grading, strength margin, and structural material efficiency; next account for curing and stored carbon; and only afterward claim avoided repair. Healing and sensing should be justified by durability and risk reduction, not used to distract from an unnecessarily carbon-intensive matrix.

C. Strength–Carbon Trade-Off

All scenarios remain above the 45 MPa screening constraint, but the lowest-carbon option has the smallest margin. The bubble size in Fig. 5 represents modeled service life, and color represents crack closure. C3 and C4 occupy a useful multifunctional region: their GWP is roughly 38–40% below C0, strength is 49–50 MPa, and modeled closure exceeds 70%. C4 has higher cost and slightly higher GWP than C3 because of the sensing network, but it provides condition information and a longer modeled inspection-informed life.

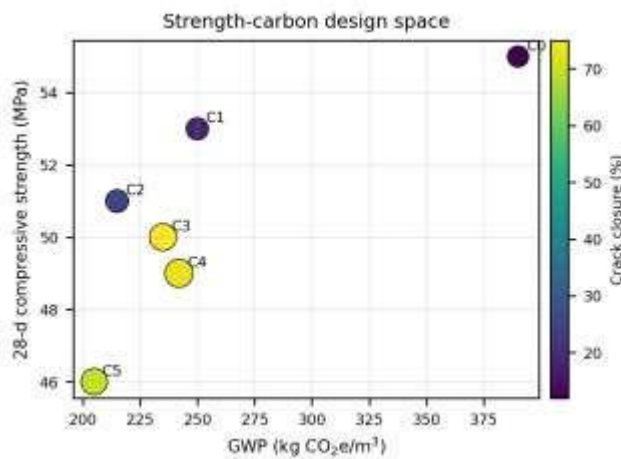


Fig. 5. Illustrative strength–carbon design space; marker size denotes modeled service life.

A single “best” mixture does not emerge. C2 is attractive for ordinary precast work where low carbon and familiar quality control dominate. C3 is preferred for inaccessible water-retaining or chloride-exposed elements where leakage or repair is costly. C4 is justified for critical assets where measurement can change inspection or maintenance decisions. C5 remains a development candidate because printability and interlayer performance add uncertainty.

D. Healing Kinetics

The screening kinetics in Fig. 6 show the strong influence of initial crack width. With adequate moisture, 0.15-mm cracks approach near-complete surface closure, while 0.80-

mm cracks remain partially open. The model should not be extrapolated to moving structural cracks. Practical design should combine crack-width control by reinforcement or fibers with a healing target; autonomous repair is not a substitute for serviceability design.

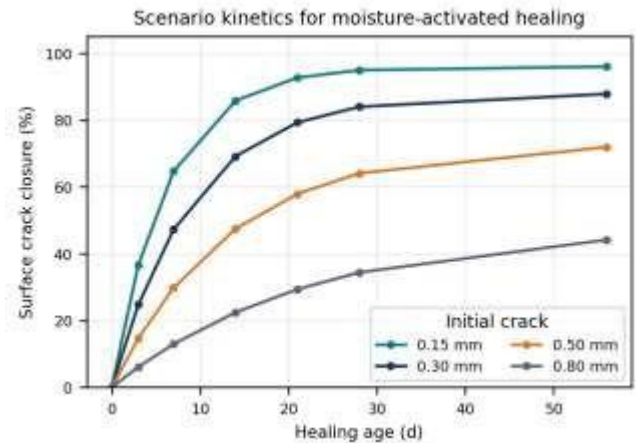


Fig. 6. Illustrative crack-closure kinetics for different initial crack widths.

Repeated exposure introduces additional constraints. A capsule may be consumed at first cracking, whereas a vascular or microbial reservoir can remain active if nutrients and moisture persist. Verification should therefore include at least one reopen–heal cycle for applications that expect fatigue or thermal movement. Functional sealing is reported beside closure, and both are stratified by initial crack width.

E. Sensing Response

The illustrative calibration in Fig. 7 uses a moderate gauge factor and displays an uncertainty band representing moisture and temperature effects. The signal is monotonic under the modeled loading range, but the environmental band becomes comparable with low-strain changes. This supports the use of differential electrode zones, colocated temperature and humidity sensors, periodic zero-load baselines, and multivariate compensation. A practical system should output both an estimate and confidence interval.

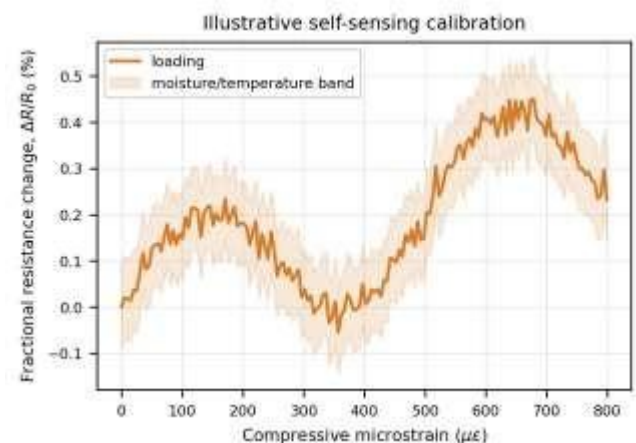


Fig. 7. Illustrative piezoresistive calibration with environmental uncertainty band.

Damage detection can use persistent residual resistance after unloading, changes in hysteresis, or spatial differences among electrode paths. Healing complicates interpretation because crack sealing may partially restore conductivity without restoring stiffness. The digital twin should therefore maintain separate states for mechanical damage, moisture, temperature, and healed transport function. Resistance alone cannot certify structural recovery.

VII. DURABILITY AND SERVICE-LIFE INTERPRETATION

A. Transport Recovery Versus Mechanical Recovery

Self-healing is most mature as a sealing technology. Mineral precipitation can reduce water flow and ion ingress even when tensile strength is not fully restored. This distinction is beneficial for durability design: slowing chloride or water transport can defer reinforcement corrosion or leakage without implying that a fractured load path is new. Structural design should continue to rely on reinforcement, fibers, redundancy, and inspection unless mechanical recovery is directly demonstrated under the relevant load history.

B. Exposure-Specific Performance

In chloride environments, healing must survive wetting–drying and salt exposure and should be evaluated using chloride profiles or migration after cracking and healing. In carbonation exposure, the low-clinker pore solution, crack geometry, and carbonation-curing history affect passivation. In sulfate or acid exposure, precipitated carbonate may not remain stable. Freeze–thaw cycling can reopen sealed cracks, while high temperature can reduce microbial viability or damage carriers. A technology validated in continuous laboratory water cannot be assumed effective in all field exposures.

C. Normalized Functionality

The normalized indices in Fig. 8 are decision aids, not measured properties. LC3-based scenarios improve the assumed chloride and water-tightness indices; healing scenarios add crack recovery; and C4/C5 add sensing stability. The chart exposes imbalance: the OPC control is strong and economical but carbon-intensive and functionally passive, while C4 is multifunctional but carries cost and calibration burdens. Decision makers can adjust thresholds without hiding these trade-offs.

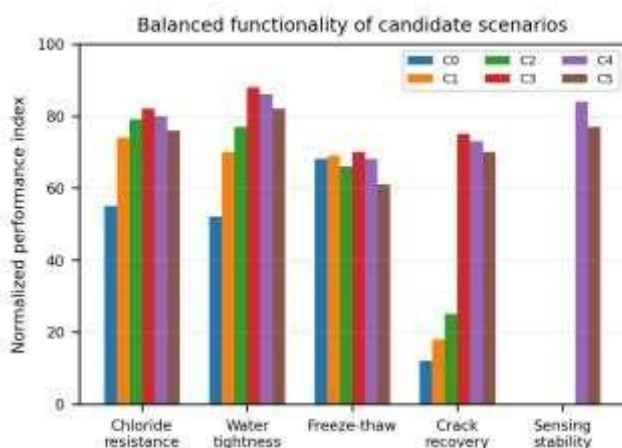


Fig. 8. Normalized functional performance indices used for scenario screening.

D. Reliability Model

A probabilistic service-life calculation should sample cover depth, surface chloride, diffusion coefficient, crack occurrence, healing success, reopening, and threshold chloride. Healing success is treated as a conditional random variable linked to crack width and moisture. Sensing reduces epistemic uncertainty only if it is calibrated, operational, and connected to an inspection action. The probability of corrosion initiation by time t is:

$$Pf(t) = P[C(xc, t) \geq C_{crit}] \quad (11)$$

Maintenance planning can minimize expected life-cycle cost by balancing inspection, false alarms, missed damage,

repair timing, and disruption. This moves multifunctional concrete from a material demonstration to an infrastructure decision system.

VIII. LIFE-CYCLE COST, CIRCULARITY, AND RISK

A. Whole-Life Cost

Initial cost premiums arise from calcined-clay quality control, healing carriers, conductive fillers, electrodes, data acquisition, and additional testing. These premiums are rational only where they reduce expected repair, outage, leakage, or inspection costs. Net present cost is evaluated as:

$$LCC = C_0 + \sum_t \frac{C_{repair,t} + C_{inspect,t} + C_{delay,t}}{(1+r)^t} - \frac{RV}{(1+r)^T} \quad (12)$$

The discount rate r strongly affects the value of distant repairs; a high rate can make durability innovation appear unattractive even when physical resource savings are substantial. Report undiscounted material and carbon flows alongside monetary results. For public infrastructure, distributional impacts such as traffic disruption, worker exposure, and service continuity may justify a societal-cost perspective.

B. Circularity and End of Life

Recycled aggregate and fines retain mineral value but can also concentrate variability, chlorides, or contaminants. Conductive and healing additions should be assessed for effects on crushing, sorting, dust, leaching, and reuse. A digital material passport can store mixture composition, test results, sensor layout, repairs, and deconstruction information. Carbonation of recycled concrete fines can provide additional mineral storage, but double counting between product stages must be avoided.

C. Environmental and Biosafety Risk

Biological systems require non-pathogenic strains, containment logic, nutrient and by-product assessment, and compliance with local biosafety rules. Urea hydrolysis can generate ammonia, creating environmental and worker concerns. Nanocarbon powders require dust control and occupational exposure procedures. Biochar must be screened for polycyclic aromatic hydrocarbons and feedstock contaminants. Data systems introduce cybersecurity, ownership, retention, and false-alarm risks. Innovation readiness therefore includes environmental, health, safety, and data governance—not only compressive strength.

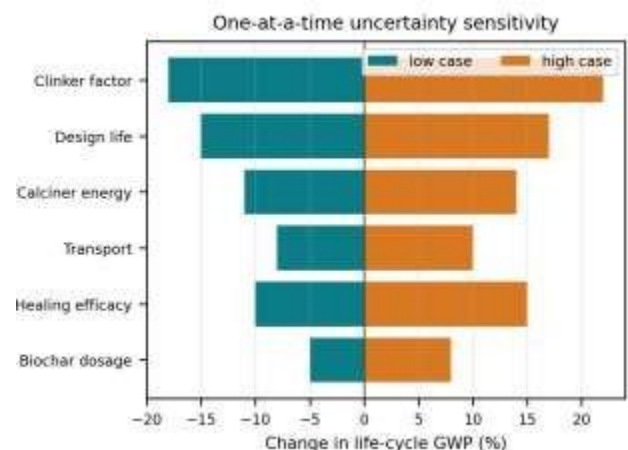


Fig. 9. Illustrative sensitivity of whole-life GWP to uncertain design assumptions.

The sensitivity plot identifies clinker factor and design life as dominant variables. The result cautions against precise claims based on uncertain healing success or biochar credit

while ignoring binder composition. Transport can also reverse the benefit of recycled aggregate when processing is distant. Report central, low, and high cases and disclose which variables are directly measured.

IX. CONSTRUCTABILITY AND QUALITY ASSURANCE

A. Conventional Casting and Precast Production

The near-term deployment route is controlled precast production. It offers stable moisture conditioning, automated dosing, protected curing, controlled CO₂ exposure, repeatable electrodes, and traceable batches. Trial production should examine scale-dependent dispersion, mixer wear, capsule breakage, pump pressure, finishing, and curing. Acceptance testing adds electrical resistivity maps and healing-carrier checks to standard fresh and strength tests. Statistical process control can detect drift in clay reactivity, aggregate moisture, and conductive dispersion.

B. Ready-Mixed Concrete

Ready-mixed deployment is more demanding because haul time, temperature, moisture, and field water additions vary. Conductive dispersion may degrade during transport, and fragile carriers may experience prolonged shear. The mix should include a documented maximum revolution count, temperature range, slump-retention window, and prohibition on uncontrolled water addition. Portable resistivity or impedance measurements can serve as process indicators but must be correlated with hardened performance.

C. 3-D Printing

For printing, the proposed modules should be introduced sequentially. First establish a printable LC3 mortar; then add low-volume carbon filler and verify pressure and filament stability; next integrate healing carriers that can pass the pump and nozzle; finally add sensing electrodes or printed conductive paths. A one-step fully multifunctional formulation risks confounding failure modes. Structural testing must include interlayer bond, anisotropic shrinkage, voids, reinforcement interfaces, and durability perpendicular to layers [23]–[25].

TABLE V
PRODUCTION QUALITY-CONTROL PLAN

Control point	Measurement	Action limit concept
Incoming clay	Reactivity, moisture, fineness	Reblend or adjust sulfate/admixture
Aggregate/biochar	Absorption and moisture	Correct effective water
Conductive slurry	Resistivity and visual dispersion	Redisperse or reject
Capsule addition	Breakage index	Reduce shear / change timing
Fresh concrete	Flow, air, temperature	Adjust within approved window
Hardened lot	Strength + resistivity COV	Hold lot for investigation
Printed layer	Width, height, interval	Pause and correct process

X. DIGITAL TWIN AND DATA ARCHITECTURE

A. Data Layers

The material passport contains immutable batch data: constituent lots, quantities, environmental factors, moisture corrections, mixer sequence, curing, geometry, electrode positions, and test results. The operational layer contains time-stamped resistance or impedance, temperature,

humidity, loading context, inspection notes, and maintenance events. A model layer estimates strain, damage state, transport risk, and uncertainty. Separating these layers prevents raw evidence from being overwritten by revised algorithms.

B. Calibration and Drift Management

Calibration begins on companion specimens and continues during proof loading. Environmental baselines are updated only during defined low-load periods. Drift thresholds trigger inspection rather than automatic structural conclusions. Missing data, sensor saturation, electrode corrosion, and communication loss are explicit states. Model performance is evaluated by false-alarm rate, missed-event rate, localization accuracy, and uncertainty calibration, not only coefficient of determination.

C. Decision Rules

A simple tiered rule is preferable to an opaque alarm. Level 0 indicates normal environmental variation; Level 1 indicates persistent resistance change requiring data review; Level 2 combines electrical change with visible cracking, leakage, or load anomaly and triggers inspection; Level 3 indicates confirmed structural distress and engineering action. Healing is logged as a state transition only after functional evidence—such as reduced leakage or stabilized transport proxy—is obtained.

XI. IMPLEMENTATION FOR INDIAN INFRASTRUCTURE

A. Material Availability and Climate

India combines high infrastructure demand, diverse clay resources, established cement manufacturing, and climates ranging from hot-dry to marine and monsoon. LC3 is particularly relevant where suitable low-grade kaolinitic clay and limestone can be processed close to cement markets. However, regional characterization is essential. High temperatures alter setting and sensor resistance; monsoon cycles may support healing but also accelerate ingress through open cracks; coastal exposure demands chloride-specific validation; and arid regions may lack the moisture needed to activate autonomous repair.

B. Priority Demonstrators

Appropriate first demonstrators are precast drains, non-prestressed façade or barrier panels, utility chambers, water-retaining secondary elements, and selected bridge parapets or deck panels with accessible inspection. These applications allow controlled production and meaningful leakage, crack, or sensing observations without relying on unvalidated self-repair for primary safety. A second stage can address marine components, tunnel linings, and critical bridge elements after long-duration durability and monitoring evidence accumulates.

C. Standards and Procurement

Prescriptive cement limits can inhibit low-clinker mixtures even when performance is adequate. Procurement should specify strength class, exposure, transport resistance, shrinkage, crack-width control, healing metric, sensing reliability, and verified GWP. Existing methods—compressive strength, sorptivity, chloride migration, resistivity, freeze-thaw, and LCA standards—can be combined with project-specific healing and sensing protocols until harmonized standards mature. Independent verification

is especially important for carbon-storage and service-life claims.

TABLE VI
STAGED TECHNOLOGY-READINESS GATES

Stage	Scale	Evidence gate	Decision
0	Paste/mortar	Compatibility and safety	Reject incompatible modules
1	Concrete specimens	Strength, transport, healing, sensing	Select Pareto candidates
2	Full-size element	Cracking, load, curing, signal stability	Approve pilot
3	Field pilot	Seasonal data and constructability	Approve limited use
4	Portfolio	Whole-life performance and MRV	Performance specification

XII. MULTI-CRITERIA RESULTS AND DECISION GUIDANCE

The radar comparison in Fig. 10 summarizes the central decision. The reference mixture retains advantages in strength familiarity and initial cost. The integrated hybrid is substantially better in modeled carbon, healing, and sensing, while remaining competitive in strength and printability. Such a chart should never replace threshold checks; it communicates why a more expensive mixture may be rational for an exposure-critical, hard-to-inspect asset.

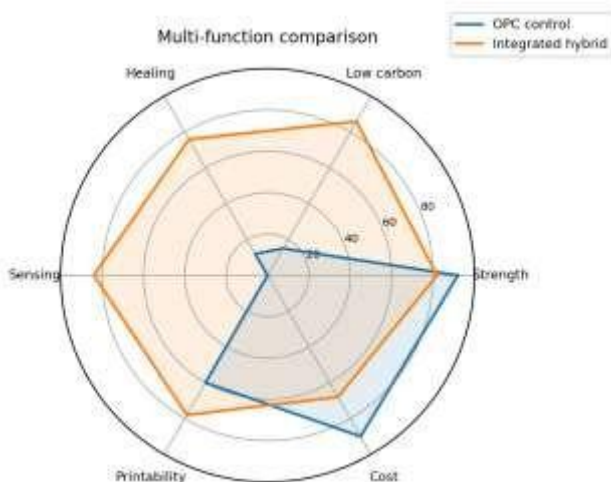


Fig. 10. Illustrative multi-criteria comparison of the OPC reference and integrated hybrid.

A. Recommended Selection Logic

Use C1 or C2 when carbon reduction is the main objective and conventional inspection is adequate. Use C3 when crack sealing directly protects service—water tightness, chloride resistance, or inaccessible surfaces—and verify the target crack class. Use C4 when condition information can change maintenance decisions and a data owner is funded for the design life. Use C5 only after printability, anisotropy, reinforcement, and field durability are validated. Reject any mixture that meets a weighted score while failing a mandatory structural, durability, environmental, or constructability threshold.

B. Contribution of Integration

Integration creates both synergy and conflict. LC3 and biochar reduce carbon but modify alkalinity, moisture, and early hydration. Moisture that activates healing also affects resistive sensing. Conductive fibers can bridge microcracks and support sensing, yet may interfere with capsule survival or pumping. Sensor data can verify cracking and the timing of healing, providing evidence unavailable from occasional

inspection. Digital optimization can find viable ranges, but only experiments expose dispersion, survivability, and scale effects. The framework makes these couplings visible before field deployment.

XIII. LIMITATIONS

First, the scenario values are illustrative and must not be cited as experimental results. Second, environmental factors vary by electricity grid, transport, plant efficiency, allocation, and material source. Third, crack-closure kinetics are simplified and do not capture irregular three-dimensional cracks, bacterial transport, precipitation clogging, or cyclic opening. Fourth, the service-life model uses idealized diffusion and does not resolve all exposure mechanisms. Fifth, sensing performance is strongly specimen- and electrode-specific. Sixth, the economic assessment omits project-specific disruption and data-management costs. Finally, standards and commercial availability continue to evolve, so the framework should be updated as validated datasets and field evidence grow.

XIV. RESEARCH ROADMAP

A. Near Term: 0–2 Years

Establish regional LC3 feedstock maps and environmental inventories; develop robust dispersion and capsule-survival methods; compare biological and inorganic healing routes; and publish open, batch-resolved datasets. Round-robin testing should focus on crack creation, image registration, permeability recovery, and electrical calibration. A reference electrode geometry and moisture-conditioning protocol would improve comparability across laboratories.

B. Medium Term: 2–5 Years

Construct full-scale precast demonstrators and expose them to realistic chloride, wet-dry, thermal, and load cycles. Integrate sensing with independent strain and crack measurements. Quantify whether monitoring changes inspection or repair decisions. Develop performance specifications that combine low GWP with transport resistance and controlled crack behavior. Validate recycling, leaching, biosafety, and occupational controls.

C. Long Term: 5–10 Years

Deploy portfolio-scale pilots with digital material passports, auditable carbon accounting, and long-duration maintenance records. Link field evidence to reliability-based codes. Advance robotic placement of functionally graded material so healing reservoirs and sensing networks are concentrated where cracks are likely rather than uniformly distributed. The long-term objective is not concrete containing the maximum number of additives; it is minimum-impact infrastructure with verified performance and information throughout its life.

XV. CONCLUSION

A credible next-generation concrete must be designed as a system. The low-carbon matrix provides the largest immediate emissions reduction; healing protects transport-controlled durability; sensing converts distributed material response into actionable information; and digital optimization manages the trade space. The proposed LC3-based platform demonstrates how these modules can be combined without claiming that one formulation suits every application.

The illustrative scenario study shows that a multifunctional candidate can remain above a 45 MPa screening strength while reducing modeled cradle-to-gate GWP by roughly 38–47% relative to the OPC reference. These values are hypotheses for validation, not laboratory findings. The most defensible pathway begins with locally characterized LC3, adds healing only for a defined crack and exposure class, adds sensing only where a data-supported maintenance decision exists, and treats printing as a separately qualified process.

Future work should prioritize functional recovery, repeated cracking, environmental compensation, batch variability, full-scale constructability, and whole-life verification. When these evidence gates are met, integrated concrete can evolve from a collection of novel ingredients into a measurable, maintainable, and lower-carbon civil-infrastructure platform.

APPENDIX A — DETAILED VERIFICATION PROTOCOL

A. Specimen Matrix

A minimum screening campaign contains the OPC control, LC3 baseline, and each integrated candidate. Three independent batches are recommended. Each batch supplies compressive-strength specimens at five ages; transport specimens in uncracked, cracked, and healed states; prism or beam specimens for cyclic sensing; and companion material for microscopy and chemical analysis. Crack-width strata and conditioning regimes are randomized across batches. Printed variants include at least three orientations and two interlayer times.

B. Crack Imaging

Mark a fixed region of interest, control illumination and camera distance, include a calibrated scale, and register images before segmentation. Report mean width, maximum width, length-weighted width, and closed area rather than a single convenient point. A blinded analyst checks automated segmentation. Publish representative failures as well as successful closure. Couple image closure with permeability or transport recovery on the same specimen where geometry permits.

C. Electrical Measurement

Use shielded leads and a four-terminal arrangement. Record electrode material, geometry, spacing, excitation amplitude and frequency, sampling rate, filtering, temperature, relative humidity, saturation state, and age. Precondition specimens to a defined moisture range. Conduct at least ten loading cycles before calibration and retain later cycles for validation. Report gauge factor, nonlinearity, hysteresis, repeatability, drift per day, signal-to-noise ratio, and prediction error on blind cycles.

D. Carbon Accounting

Use supplier-specific environmental declarations where compatible; otherwise document database version, geography, allocation, and uncertainty. Separate fossil and biogenic carbon. Verify biochar carbon content and stable fraction; do not credit avoided biomass decay unless the counterfactual is justified. Measure CO₂ supplied and vented during curing and subtract compression and capture energy. State whether carbonation at use and end of life is included. Report both per cubic metre and per unit of structural or durability function.

TABLE VII
CORE VARIABLES FOR A REPRODUCIBLE DATASET

Variable	Symbol	Unit	Suggested screening range
Total binder	B	kg/m ³	340–460
Water/binder	w/B	—	0.30–0.45
Clinker fraction	f _{cl}	% binder	45–75
Biochar	f _{bc}	% binder	0–2
Healing carrier	f _h	% volume	0–5
Conductive filler	f _c	% binder	0–1.5
Recycled coarse aggregate	RCA	% coarse aggregate	0–50
Target crack width	w ₀	mm	0.10–0.80
CO ₂ curing time	t _c	h	0–24
Electrode spacing	L _e	mm	50–250

APPENDIX B — FAILURE MODES AND CONTROLS

TABLE VIII
FAILURE-MODE-AND-CONTROL REGISTER

Failure mode	Consequence	Detection	Preventive control
Clay under-calcined	Low reactivity; strength loss	XRD/TGA; reactivity test	Controlled calcination and blending
High water absorption	Effective w/B drift	Moisture and absorption tests	Preconditioning and batch correction
Capsule rupture in mixer	Healing reserve consumed	Microscopy / release tracer	Late addition; lower shear
Bacterial viability loss	Low mineral precipitation	Culture or molecular assay	Protected carrier; temperature control
Carbon agglomeration	Weak zones; noisy sensing	Resistivity COV; microscopy	Controlled dispersion energy
Electrode polarization	Apparent resistance drift	Frequency sweep	Four-probe AC measurement
Moisture cross-sensitivity	False strain/damage alarm	Humidity compensation test	Co-located T/RH sensors
Printed cold joint	Anisotropic leakage/failure	Bond and permeability tests	Layer-time control; surface activation
Unverified carbon credit	Misleading GWP claim	Inventory audit	Measured uptake and conservative boundary
Model extrapolation	Unsafe optimum	Domain and uncertainty checks	Physics constraints; targeted experiments

APPENDIX C — EXAMPLE PERFORMANCE SPECIFICATION

The following project language illustrates a performance-based approach. It is not a substitute for structural design or local code: “Provide concrete achieving characteristic compressive strength not less than the project value; maximum crack width not exceeding the serviceability limit; 28-day transport indicator meeting the exposure-specific threshold; verified cradle-to-gate GWP not exceeding the declared limit under the stated product-category rules; and fresh properties compatible with the approved placement method. Where autonomous healing is claimed, demonstrate median permeability recovery and confidence bounds for the specified crack-width class and conditioning regime. Where self-sensing is claimed, demonstrate blind-cycle strain or damage classification error, drift, and temperature/moisture compensation. Submit constituent traceability, batch records, environmental inventory, calibration files, and field acceptance procedures.”

APPENDIX D — EXTENDED STATE-OF-THE-ART SYNTHESIS

This appendix expands the evidence basis behind the integrated framework. It is organized by engineering question rather than by publication chronology. Each subsection identifies the constituent-scale mechanism, the evidence

needed for validation, interactions with other modules, and the practical condition that should control deployment. The purpose is to prevent an apparently successful result in one test from being generalized to a complete concrete system.

A. Calcined-Clay Selection

Calcined clay is not a single standardized powder. Its performance depends on kaolinite content, associated quartz or iron minerals, calcination temperature, residence time, cooling, grinding, and storage. The same nominal replacement can therefore produce different water demand, reaction rate, color, setting, and long-term transport properties.

Mineralogical screening should combine raw-clay characterization with a reactivity test and trial mortar. Over-calcination can reduce reactivity by forming less reactive phases, while under-calcination leaves untransformed clay. Particle fineness may accelerate reaction but also increases surface area and superplasticizer demand.

For the integrated mixture, clay selection affects every module. Early pore-solution chemistry influences bacterial survival and carbonate precipitation; water demand affects biochar conditioning; and ionic conductivity shifts the baseline of resistive sensing. A clay that performs well in a binary paste may not be optimal after these additions.

A procurement specification should identify the quarry and processing route, define lot-based limits for moisture and fineness, and require a performance envelope for strength and transport. When source variability is large, controlled blending and rapid reactivity checks are more reliable than a fixed chemical-oxide limit alone.

B. Limestone Fineness and Sulfate Balance

Limestone in LC3 is both filler and reactive participant. Fine particles improve packing and supply carbonate that stabilizes carboaluminate phases. The limestone-to-alumina balance and gypsum addition influence early reaction, ettringite formation, workability retention, and dimensional stability.

Isothermal calorimetry, bound-water or thermogravimetric measurements, and compressive strength across several sulfate dosages can identify a suitable window. The optimum is not necessarily the dosage that produces the highest one-day heat; excessive sulfate or an incompatible admixture can create delayed response or poor retention.

Healing carriers and carbon dispersants add surfaces that can adsorb sulfate or admixture molecules. Their inclusion may shift the optimum determined for the base LC3 paste. The sulfate study should therefore be repeated at least at the selected integrated dosage rather than assumed unchanged.

Production control should record limestone mineralogy, fineness, and moisture. If limestone is co-ground, grinding energy and particle-size coupling must be considered. If separately blended, feeder accuracy becomes critical because small errors can change both rheology and phase assemblage.

C. Recycled Coarse and Fine Aggregate

Recycled aggregate closes a material loop but usually contains attached mortar, higher absorption, lower density, and greater variability than virgin aggregate. Its environmental advantage depends on avoided landfill, local processing, replacement of virgin material, transport distance, and whether extra cement is required to recover strength.

Characterization includes grading, density, absorption, adhered mortar, crushing resistance, chlorides, sulfates,

contaminants, and moisture. A two-stage mixing or preconditioning procedure can reduce uncontrolled water uptake. Recycled fines require particular attention because they strongly affect rheology and may contain hydrated cement capable of additional carbonation.

In a sensing mixture, variable moisture and ionic content can dominate electrical resistance. In a healing mixture, porous recycled particles may act as reservoirs but can also create weak interfaces and wider cracks. Their role should be deliberately designed rather than treated as a simple mass substitution.

A local break-even transport analysis is needed. Recycled aggregate hauled from a distant centralized plant may have little carbon advantage over nearby natural aggregate. The most defensible use case combines local demolition feedstock, controlled processing, moisture correction, and no compensating increase in clinker content.

D. Biochar Source, Processing, and Conditioning

Biochar properties reflect feedstock, pyrolysis temperature, heating rate, residence time, activation, grinding, and storage. Wood-derived and agricultural-residue chars can differ substantially in ash, pore structure, carbon stability, pH, and contaminants. Consequently, dosage by mass alone is insufficient for transfer between studies.

A complete characterization reports dry density, particle size, BET or accessible surface area where available, water absorption kinetics, ash, elemental carbon, volatile matter, pH, electrical conductivity, and relevant contaminants. Carbon permanence should be estimated using an accepted method rather than assumed from total carbon.

Pre-saturation can reduce fresh water demand and support internal curing, but it changes the effective water balance. Fine biochar may participate in the conductive network, altering percolation and gauge factor. Its alkalinity and adsorptive surface may also affect admixture efficiency and the nutrient environment of microbial healing.

The optimum practical dose is typically a narrow range found by performance testing. A credible claim shows the response curve—including strength or workability loss at excessive dosage—rather than reporting only the best point. Feedstock traceability and a contaminant certificate are essential for large-scale procurement.

E. Carbonation Curing and Mineralized CO₂

Accelerated carbonation curing is most controllable in precast units, blocks, recycled fines, or thin sections. Uptake depends on pore saturation, CO₂ concentration and pressure, temperature, exposure time, specimen geometry, and the availability of reactive calcium phases. Fully saturated pores inhibit gas transport, while very dry pores limit dissolution.

Measurement should separate true reaction uptake from moisture loss or gas held in voids. Direct gas mass balance, thermogravimetric carbonate quantification, and controlled reference specimens provide complementary evidence. Strength, shrinkage, permeability, and later hydration are tested after carbonation, not inferred from uptake.

In LC3, the reduced clinker fraction changes the amount and type of carbonatable phases. Early carbonation may modify pore solution and passivation, which matters for reinforced products. It may also change the electrical baseline and the calcium supply available for later crack healing.

Life-cycle accounting includes captured CO₂ origin, purification, compression, transport, curing-chamber electricity, leakage, rejected products, and verified storage.

The stored quantity is not automatically equal to supplied gas. A conservative declaration credits only measured stable uptake within the stated system boundary.

F. Microbial Healing Pathways

Microbial healing uses spores or cells capable of surviving alkaline cement environments and producing carbonate under activation conditions. Ureolytic pathways can precipitate calcium carbonate rapidly but may generate ammonium. Alternative metabolic pathways use lactate, nitrate, or other substrates and must be assessed for kinetics, by-products, and compatibility.

Validation begins with strain identity, non-pathogenic status, viable count, carrier loading, storage stability, and survival after mixing. Concrete testing then links viable or metabolic activity to mineral identity and functional sealing. A white precipitate or reduced visible width alone does not prove a microbial mechanism.

LC3 pore chemistry, biochar surfaces, curing, and moisture affect viability. A conductive network can monitor crack formation, but electrical change during wet healing may reflect ionic conduction rather than mineral bridging. Biological, chemical, hydraulic, and electrical measurements should be interpreted together.

Deployment should select a target crack-width distribution and exposure. Systems dependent on continuous water may perform well in tanks or marine splash zones but poorly in sheltered dry elements. Nutrient release, ammonium, leaching, and long-term ecological behavior require project-specific environmental review.

G. Capsules and Inorganic Healing Agents

Capsules isolate a liquid, powder, or microbial payload until a crack intersects the shell. Their effectiveness depends on shell strength, bond with the matrix, size distribution, dosage, spatial probability of crack intersection, agent viscosity, reaction time, and compatibility with moisture and temperature.

A good capsule survives handling and mixing but ruptures under crack opening. This conflict is quantified through single-particle crushing, mixer-recovery counts, microscopy of hardened sections, release tracers, and controlled fracture. Capsule volume must be included in the absolute-volume calculation because it can displace load-bearing paste or aggregate.

Capsules may interrupt a conductive network or become sites of stress concentration. Conversely, short conductive fibers may bridge cracks and reduce the opening needed to rupture a capsule. Co-design should therefore examine crack geometry and healing activation at the same filler and fiber dosage used for sensing.

One-shot capsules are best suited to isolated cracking events. Repeated movement may consume the local reservoir and reopen the seal. Acceptance tests should include at least one reopen cycle or explicitly state that the system provides only first-event sealing.

H. Fiber-Based Crack-Width Control

Fibers do not replace conventional reinforcement, but suitable microfibers can distribute cracks and limit individual width. This improves healing probability because multiple small cracks are generally easier to seal than one localized wide crack. Fiber type, aspect ratio, bond, orientation, and volume govern the response.

Flexural toughness, residual strength, direct tension where feasible, and image-based crack mapping reveal more than compressive strength. For printed material, extrusion aligns fibers and creates directional properties; specimens must be tested in more than one orientation.

Carbon fibers can contribute simultaneously to crack control and conductivity, yet their dispersion is difficult and their surface chemistry affects bond. Polymer fibers support crack control without creating the same electrical network. A hybrid design may separate the mechanical and sensing roles to improve robustness.

The design sequence should set the serviceability crack-width target first, then choose fibers and reinforcement, and finally size the healing system for the residual crack class. Claiming that healing will correct poorly controlled structural cracking reverses sound engineering logic.

I. Conductive Percolation Network

Electrical behavior changes sharply near the percolation threshold. Below it, isolated particles give high resistance and unstable conduction; near it, small changes in contact or tunneling distance produce high sensitivity; far above it, conductivity is stable but gauge sensitivity may fall. The useful range depends on filler morphology and matrix moisture.

A dosage sweep should measure fresh dispersion, hardened DC and AC behavior, spatial variability, mechanical properties, and rheology. Reporting only the best gauge factor can hide excessive hysteresis, drift, or specimen-to-specimen variation. Four-probe measurements and frequency sweeps reduce electrode artifacts.

Biochar, carbon black, short carbon fibers, steel fibers, and pore solution can all contribute to conduction. LC3 hydration changes ionic conductivity with age. Healing introduces water and carbonate across the crack. The baseline must therefore be age- and moisture-specific, and the digital model should identify its valid domain.

Scale-up requires reliable electrodes, cable protection, channel identification, and replaceable acquisition hardware. The concrete may last decades longer than the electronics. A maintenance plan should allow data equipment to be renewed without losing batch metadata and calibration history.

J. Electrode Geometry and Impedance

Electrodes define the measurement volume. Two-probe measurements mix bulk resistance with contact resistance and polarization, while four-probe arrangements better isolate the material response. Stainless steel mesh, bars, plates, or conductive coatings each create different field distributions and durability concerns.

Geometry is recorded with drawings and as-built coordinates. Calibration considers electrode spacing, embedment, cover, orientation relative to expected cracks, and reinforcement interference. Alternating-current impedance across a controlled frequency band can distinguish bulk and interfacial effects more effectively than a single resistance value.

Crack localization improves when multiple overlapping paths are available, but more channels increase wiring and data complexity. Printing may enable embedded conductive paths or precisely placed electrodes; conventional casting may favor robust mesh or bar contacts. Both require continuity checks before and after placement.

Electrode corrosion or debonding can mimic concrete damage. Reference resistors, redundant paths, insulation

checks, and periodic impedance diagnostics help distinguish hardware failure. Alarm rules should include a sensor-health state instead of forcing every anomaly into a structural interpretation.

K. Printable Rheology and Buildability

Printable concrete must flow through the delivery system under applied shear and rapidly regain yield stress after deposition. Pumpability, extrudability, shape stability, open time, and buildability are related but distinct. A mixture can extrude smoothly yet slump after several layers, or build well but require damaging pressure.

Rheological tests are paired with process measures: pressure, flow rate, nozzle speed, filament width and height, layer deformation, and maximum stable height. The test equipment and shear history should resemble the production system because small laboratory mixers may not reproduce pumping and hose effects.

Calcined clay increases thixotropy and water demand; carbon fillers add surface area; fibers align and may block; capsules may break; recycled fines alter particle packing. A printable base matrix should be stabilized before multifunctional additions are introduced one at a time with requalification after each change.

Buildability is a time-dependent structural problem. Ambient temperature, wind, layer interval, and early hydration determine green strength. Field control should monitor material temperature and layer geometry continuously and define a pause-and-restart procedure for interruptions.

L. Interlayer Bond and Anisotropic Durability

Layer interfaces in extrusion can contain pores, drying films, segregation, or weak contact. Bond depends on time gap, surface moisture, nozzle pressure, deposition geometry, and material structuration. Mechanical anisotropy is only part of the concern; preferential water or chloride transport along interfaces can govern durability.

Testing includes direct or indirect tension, shear, flexure, permeability, sorptivity, and imaging with specimens cut in defined orientations. Reporting “printed strength” without orientation and print parameters prevents comparison. Reinforcement crossing the interface introduces another local geometry that requires testing.

Healing may be especially valuable at stable microcracked interfaces, but reservoirs must intersect those interfaces and activation moisture must reach them. Conductive paths aligned by printing may provide directional sensitivity. These potential synergies should be demonstrated rather than assumed from cast specimens.

Quality assurance uses digital toolpath records, layer time stamps, geometry scans, and material batch data. A printed element is a process product; acceptance must link the material formulation to machine settings and environmental conditions.

M. Machine Learning and Optimization

Machine learning is valuable when mixture-to-performance relationships are nonlinear and experiments are expensive. Tree ensembles, Gaussian processes, neural networks, and symbolic models can support prediction, while evolutionary or Bayesian methods search strength, carbon, cost, and durability objectives. The model does not create evidence beyond its training domain.

A useful dataset records constituent chemistry and properties, not only generic labels such as “cement” or “fly ash.” Batch, curing, specimen geometry, test method, age, and moisture are essential features. Grouped data splitting prevents specimens from the same batch appearing in both training and test sets.

Integrated concrete produces dataset shift because capsules, biochar, conductive filler, and print process are uncommon in legacy databases. Uncertainty-aware models should penalize extrapolation and recommend targeted experiments. Physics constraints enforce nonnegative quantities, volume balance, and known feasibility limits.

Optimization output is a Pareto frontier with uncertainty, not one recipe with false precision. Engineers select candidates using mandatory constraints and stakeholder priorities, then validate them experimentally. All training data, preprocessing, hyperparameters, random seeds, and evaluation partitions should be archived.

N. Life-Cycle Assessment and MRV

Life-cycle assessment is a comparison method, not a decorative carbon number. Functional equivalence, system boundary, allocation, geography, electricity, transport, strength, service life, and end-of-life assumptions must be stated. Per-cubic-metre results can mislead if mixtures provide different structural or durability function.

Measurement, reporting, and verification (MRV) are particularly important for stored carbon. Biochar requires stable-carbon and chain-of-custody evidence. Carbonation curing requires gas mass balance and energy. Natural carbonation should be reported under the life-cycle module in which it occurs and should not be double counted.

Healing benefits enter whole-life assessment through conditional repair scenarios. A laboratory closure percentage does not equal a guaranteed extension of service life. Field probability, crack distribution, exposure, reopening, and maintenance action determine the expected benefit.

Uncertainty analysis should report distributions or scenarios, not only a point estimate. When supplier-specific data are unavailable, conservative regional factors and sensitivity ranges are preferable. Independent review is advisable for public environmental claims and procurement thresholds.

O. Field Reliability and Maintenance

Field performance combines material variability, construction, exposure, structural loading, sensor hardware, communications, and organizational response. A technically capable sensing material provides no benefit if data are not reviewed or if an alarm has no funded action. Reliability therefore includes people and process.

Pilot design should define hypotheses in advance: expected crack locations, target closure or sealing, signal magnitude, seasonal drift, inspection schedule, and decision thresholds. Independent reference sensors and conventional inspections provide ground truth. Negative and ambiguous results are retained.

Data continuity requires channel maps, calibration versions, timestamps, quality flags, backup, and ownership. Algorithms can be updated, but raw data and previous model outputs remain available for audit. Cybersecurity and access control are proportionate to asset criticality.

Scaling occurs only after seasonal exposure and at least one meaningful damage or maintenance observation where possible. Portfolio adoption uses a feedback loop: field

evidence updates mixture selection, thresholds, and expected service-life distributions rather than merely confirming the original design.

APPENDIX E — WORKED ILLUSTRATIVE MIX-DESIGN AND CARBON CALCULATION

A. Provisional One-Cubic-Metre Composition

The worked example demonstrates bookkeeping for candidate C4. It is not a field-ready recipe. A provisional mixture contains 400 kg/m³ total binder divided into 200 kg clinker-rich cement component, 120 kg calcined clay, 60 kg limestone, and 20 kg gypsum or sulfate-balanced component. Effective water is 148 kg/m³, giving w/B = 0.37. The aggregate skeleton contains 690 kg/m³ fine aggregate and 980 kg/m³ coarse aggregate. Healing carrier occupies 2.5% of concrete volume, a hybrid carbon addition is 0.35% of binder mass, and high-range water reducer is adjusted through trials.

The absolute-volume calculation uses measured densities rather than nominal bulk density. Free water excludes moisture absorbed in recycled aggregate, biochar, or healing carrier. If the carrier volume is added without reducing another constituent, the batch will exceed one cubic metre and comparisons will be invalid. Entrained and entrapped air are measured and included in the closure check of (9).

TABLE IX
WORKED ILLUSTRATIVE CRADLE-TO-GATE INVENTORY FOR C4

Constituent	Mass (kg/m ³)	Example EF (kg CO ₂ e/kg)	Contribution (kg CO ₂ e/m ³)
Clinker-rich component	200	0.82	164.0
Calcined clay	120	0.18	21.6
Limestone	60	0.02	1.2
Gypsum/balance	20	0.06	1.2
Aggregates	1670	0.006	10.0
Admixture	4.8	1.50	7.2
Healing module	—	inventory	20.0
Conductive module	1.4	inventory	12.0
Mixing/transport	—	inventory	18.0
Verified storage credit	—	measured	-13.2
Total	—	—	242.0

B. Interpretation of the Inventory

The example total matches the 242 kg CO₂e/m³ scenario value, but the emission factors are placeholders. The clinker-rich component remains the dominant contribution. Healing and conductive modules together contribute 32 kg CO₂e/m³, showing why they should be used selectively. The storage credit is smaller than the mass of biochar or supplied CO₂ because only verified stable carbon inside the stated boundary is credited.

If strength falls below the 45 MPa constraint, increasing clinker is not the only response. Aggregate packing, curing, calcined-clay reactivity, sulfate balance, admixture compatibility, and air should be investigated first. A mixture with excess cement may satisfy strength but undermine the main carbon objective. Conversely, a very low-carbon mixture that requires greater member size or early repair may lose its advantage at structural scale.

C. Example Multi-Criteria Ranking

For demonstration, normalize strength, carbon, relative cost, crack closure, and service life across C0–C5. Apply mandatory constraints first: $f_c \geq 45$ MPa; placement window

achieved; no durability indicator below the project minimum; and no unresolved environmental or biosafety issue. Only feasible candidates proceed to ranking. Suppose a coastal utility structure uses weights of 0.30 carbon, 0.15 cost, 0.15 strength margin, 0.25 durability/healing, and 0.15 monitoring value. C3 and C4 become leading candidates, while C2 remains a useful low-cost alternative.

Change the application and the ranking changes. For an ordinary indoor precast panel, monitoring has little value and C2 may dominate. For a tunnel segment where inspection access is limited, the expected value of sensing and sealing can justify C4. The calculation is therefore a transparent conversation about asset needs, not a universal material league table.

D. Batch Scaling and Moisture Example

Assume recycled coarse aggregate in a trial batch has 5.0% absorption and 3.5% actual moisture relative to oven-dry mass. The aggregate is 1.5 percentage points below saturated-surface-dry condition and will absorb water during mixing. For 300 kg/m³ oven-dry recycled aggregate, the potential absorption correction is 4.5 kg/m³. That water is added or the aggregate is preconditioned, while the effective w/B remains 0.37. The same logic is applied separately to biochar and porous healing carriers using their measured absorption kinetics.

$$W_{\text{correction}} = mOD(A - MC)/100 \quad (13)$$

Moisture correction is not a minor production detail. A 4.5 kg/m³ error changes w/B by about 0.011 for a 400 kg/m³ binder system. That shift can alter slump, strength, transport, ionic conductivity, and healing activation. Every multifunctional test result should therefore retain the actual aggregate and carrier moisture record.

E. Example Healing Acceptance Calculation

Consider a 0.30-mm crack class with initial water flow $q_{\text{cracked}} = 12.0$ g/min under the specified head. After 28 days of wet-dry healing, $q_{\text{healed}} = 2.4$ g/min. Equation (10) gives 80% sealing efficiency. If median surface closure is 88%, the paired result suggests that most visible closure corresponds to reduced flow. If another specimen has 95% closure but $q_{\text{healed}} = 7.2$ g/min, sealing efficiency is only 40%; the discrepancy triggers imaging of through-crack continuity and mineral distribution.

Acceptance should use a distribution across independent batches. For example, a project may require the lower confidence bound on median or mean sealing efficiency to exceed a threshold for the specified crack class. The exact statistical form is chosen before testing. Post hoc deletion of specimens with large cracks or low closure creates an unrealistically favorable result.

F. Example Sensing Compensation

Suppose the raw fractional resistance change is 0.42%, temperature increases by 3°C, moisture proxy increases by 0.8 normalized units, and calibration coefficients are $\alpha_T = 0.03\%/^{\circ}\text{C}$ and $\alpha_M = 0.12\%$ per unit. Environmental contributions total 0.186%, leaving 0.234% for mechanical and damage effects. With GF = 45, the equivalent elastic strain estimate is about 52 microstrain if no persistent damage term is present. The digital output should retain the raw value, corrections, estimated strain, and uncertainty.

After unloading, a residual corrected change may indicate cracking, electrode change, or incomplete baseline recovery. A second channel crossing the same zone and an independent displacement or acoustic measurement help classify the event.

If healing later reduces leakage but resistance remains shifted, the system records transport recovery without claiming full mechanical restoration.

APPENDIX F — STANDARDS, DATA, AND REPORTING CHECKLIST

A. Standards Mapping

TABLE X
STANDARDS AND PROJECT-SPECIFIC EXTENSIONS

Purpose	Established method family	Project-specific extension
Compressive strength	ASTM C39/C39M or equivalent	Multiple ages; printed orientations
Water absorption	ASTM C1585 or equivalent	Cracked and healed states
Chloride indicator	ASTM C1202 / migration/profile methods	Post-healing transport recovery
Freeze-thaw	ASTM C666/C666M or equivalent	Reopening after healed crack
Structural design	ACI 318 / applicable national code	No strength credit without evidence
Life-cycle assessment	ISO 14040/14044; applicable PCR	Storage MRV and service-life scenarios
Self-healing	RILEM guidance / project protocol	Width-stratified functional recovery
Self-sensing	Electrical and SHM protocol	Four-probe compensation and blind test
3-D printing	Emerging NIST/RILEM/ACI guidance	Machine, layer, and orientation metadata

Established standards provide common mechanical, durability, and LCA foundations, but they do not automatically validate an integrated claim. A standard chloride test on uncracked concrete does not measure healing; a resistance measurement without environmental control does not validate sensing; and an EPD does not prove future repair avoidance. The project protocol links each claim to a measured quantity, comparator, exposure, and uncertainty.

B. Minimum Dataset Schema

Each observation is linked to project, material source, constituent lot, mixture ID, batch ID, specimen ID, production date, operator, equipment, curing history, orientation, preconditioning, test method version, raw file, processed result, and quality flag. Constituent records include chemistry, mineralogy, density, moisture, absorption, and environmental factor with source. Sensor records add channel, electrode geometry, excitation, sampling, temperature, humidity, and calibration version.

Identifiers are never reused. Corrections create a new version with a reason and retain the original. Units are stored explicitly, and missing values are distinguished from zero. A data dictionary defines every field, permissible range, and transformation. This discipline enables later machine learning without reconstructing undocumented assumptions from paper tables.

C. Reporting Checklist for an IEEE-Style Experimental Paper

A subsequent experimental paper should state the research question and comparator; report complete mixture proportions and constituent characterization; identify independent batches and replicate logic; describe curing, cracking, conditioning, and test equipment; provide raw or repository-linked data; and distinguish confirmatory from exploratory analysis. Figures should show distributions or uncertainty, not only representative images. Tables should include units and sample size. Any machine-learning result

should identify the test split, leakage controls, hyperparameters, and external validity.

Claims should match evidence. “Self-sealing” is preferred when permeability recovers but strength is not assessed. “Self-sensing” requires repeatable correlation and environmental compensation. “Low carbon” requires a comparable boundary and verified inventory. “Carbon negative” requires net-negative results under a complete, defensible system boundary and sensitivity analysis. “Structural” requires compliance with design and durability requirements beyond cube or cylinder strength.

D. Field Pilot Record

The pilot record begins before casting with an asset hypothesis, monitoring plan, baseline inspection, expected crack zones, environmental exposure, decision thresholds, and responsibility matrix. Production records capture every batch and any deviation. Commissioning includes proof loading or controlled response, sensor-health checks, reference measurements, and as-built geometry. Seasonal inspections synchronize visual crack maps, leakage, electrical channels, and environmental conditions.

A pilot is successful when it answers a decision question, not merely when concrete is placed. Useful outcomes include confirmation of stable dispersion, identification of excessive environmental drift, measured sealing of a known crack, evidence that an alarm caused timely inspection, or a documented failure that improves the next formulation. The report includes all outcomes and preserves the chain from constituent to maintenance action.

E. Independent Review Questions

Before a major deployment, an independent reviewer should ask: Are the material functions necessary for this asset? Are claims linked to acceptance tests? Are mixture and process variables inside the validated range? Are environmental and biosafety risks controlled? Is stored carbon measured without double counting? Does the service-life model represent the actual exposure? Can the electronics be maintained? Who owns and interprets the data? What action follows an alarm? What happens if healing or sensing fails?

A satisfactory answer may still recommend a simpler mixture. Innovation is valuable when it reduces verified impact or risk, not when it maximizes novelty. The framework therefore treats rejection, simplification, or staged introduction as successful engineering decisions.

APPENDIX G — TECHNICAL DISCUSSION AND RESEARCH NOTES

The notes below provide additional depth for researchers preparing laboratory work from this framework. They identify mechanisms and reporting choices that are frequently compressed in short papers but materially affect interpretation. These discussions are not additional scenario results; they explain how future measurements can confirm, reject, or refine the proposed architecture.

A. Hydration Thermodynamics and Phase Assemblage

Hydration of an LC3 binder involves simultaneous clinker reaction, dissolution of calcined-clay aluminosilicates, sulfate-controlled aluminate reaction, filler-assisted nucleation, and carbonate-bearing phase formation. The assemblage evolves with age and temperature. A simple clinker-replacement label cannot describe this evolution;

chemical composition, reactive fraction, sulfate, and curing must accompany mechanical results.

Thermodynamic modeling can screen plausible hydrate assemblages, but model databases and assumptions should be stated. Experimental confirmation may combine X-ray diffraction with internal standard, thermogravimetry, selective dissolution, microscopy, and pore-solution analysis. No single technique resolves all poorly crystalline phases. Agreement among mass balance, bound water, phase trends, and strength is more persuasive than an isolated diffraction peak.

Healing changes the local chemistry again. Water entering a crack dissolves ions, supports continued hydration, and enables carbonate precipitation. A microbial pathway may shift pH or carbonate availability, while accelerated carbonation curing may already have consumed some calcium-bearing phases. Crack precipitates should be compared with the surrounding matrix so that autogenous, microbial, and curing-derived carbonates are not confused.

For engineering selection, phase analysis should answer a decision question: whether an unexpected strength or transport result arises from incomplete clay reaction, sulfate imbalance, carbonation, or an additive interaction. An elaborate analytical campaign without a defined hypothesis can add attractive images without improving the mixture.

B. Pore Structure and Interfacial Transition Zones

Transport and sensing emerge from a connected pore network rather than total porosity alone. LC3 can refine capillary pores through reaction and packing, whereas porous biochar, healing carriers, and recycled attached mortar introduce internal reservoirs and interfaces. Mercury intrusion, gas sorption, water sorption, nuclear magnetic resonance, and micro-computed tomography probe different pore ranges and should not be treated as interchangeable.

The aggregate–paste and carrier–paste interfacial transition zones may govern crack initiation. A strong capsule shell with poor bond can debond rather than rupture; a highly absorptive recycled aggregate can draw water from nearby paste; and carbon-fiber bundles can create agglomerate interfaces. Polished sections across statistically selected regions help distinguish a representative mechanism from a visually dramatic local feature.

A self-healing design benefits from connected access for water and ions but a durable concrete seeks low transport connectivity. This apparent conflict is resolved by localization: water reaches a crack that is already a high-permeability path, activates a nearby reservoir, and the reaction reduces that path without requiring a generally permeable matrix. Carrier size and distribution should be optimized around probable crack spacing.

Electrical conduction adds another network. Ionic pore solution dominates at high saturation, while carbon contacts and tunneling dominate under other frequencies and moisture states. Joint pore and impedance characterization can explain why two specimens with similar DC resistance show different mechanical sensitivity or drift.

C. Fresh Rheology, Thixotropy, and Admixture Demand

Fresh behavior is controlled by particle packing, surface chemistry, flocculation, water, air, and shear history. Calcined clay and fine carbon have high surface area and may adsorb polycarboxylate molecules; biochar can absorb water; capsules and fibers increase particle interaction. A slump value recorded after one mixing sequence does not define the rheology of another sequence or a pumped process.

Flow curves, static and dynamic yield stress, plastic viscosity, thixotropic rebuilding, and hysteresis help diagnose placement. For conventional casting, the aim is stable workability without segregation. For printing, high static rebuilding supports layers while acceptable dynamic yield and viscosity limit pump pressure. Test timing after water contact and the pre-shear protocol are part of the result.

Admixture compatibility should be evaluated at realistic sulfate balance and temperature. An apparently efficient dosage at 20°C may lose retention in Jaipur summer conditions. Nutrients, surfactants used for carbon dispersion, and capsule-shell chemistry can retard or accelerate reaction. Calorimetry and setting tests should accompany rheology when an addition changes open time.

Scale-up should monitor mixer power and discharge uniformity. A laboratory dispersion method that uses sonication may not translate to a ready-mix plant. The production process must provide comparable energy without damaging capsules. The research result should therefore specify a scalable dispersion route or clearly label the method as a laboratory proof of principle.

D. Early-Age Thermal, Shrinkage, and Creep Effects

Low-clinker binders can change heat release and early strength, while fine particles and low w/B increase autogenous shrinkage risk. Biochar or prewetted porous carriers may provide internal curing, but their desorption kinetics determine effectiveness. Restraint converts shrinkage into tensile stress, creating the cracks the healing system is later asked to manage.

A robust programme records temperature, sealed autogenous deformation, drying shrinkage, mass loss, and restrained cracking. Temperature-matched curing is important for thick elements. If a mixture delays setting, the reference time for shrinkage should be defined consistently rather than taken automatically from water addition.

Creep and stress relaxation influence long-term crack width. Healing precipitation that seals an unloaded laboratory crack may behave differently under sustained opening. Crack-control specimens can be held under displacement or load during conditioning to represent realistic service states. The applied restraint and any relaxation should be measured.

The goal is to prevent avoidable early cracking while retaining autonomous capacity for unavoidable service cracks. Counting a reduction in early crack width as a healing benefit confuses prevention and repair; both are valuable but should be measured and reported separately.

E. Chloride Ingress, Carbonation, and Reinforcement Corrosion

Chloride transport depends on diffusion, capillary absorption, convection, binding, temperature, saturation, cracks, and electrical fields. Rapid electrical tests are convenient indicators but can be affected by pore-solution conductivity and conductive fillers. A low measured resistance in self-sensing concrete does not necessarily mean poor chloride resistance, so migration or profile methods require interpretation and alternative non-electrical tests may be necessary.

Carbonation reduces pore-solution alkalinity and can depassivate reinforcement. LC3 contains less clinker-derived calcium hydroxide than OPC, but pore refinement may slow carbon dioxide transport. Accelerated carbonation tests use elevated concentration that may change mechanism. Natural-

exposure correlation and moisture conditioning are needed before service-life prediction.

Cracks connect the surface to reinforcement and can dominate initiation. Healing should be evaluated with cracks crossing the cover, not only surface grooves. After conditioning, chloride profiles, steel potential, polarization resistance, or corrosion rate provide stronger evidence than surface closure. Reinforcement geometry and cover are reported.

A conductive carbon network near steel can also alter electrochemical measurement or galvanic conditions, depending on contact. Electrical isolation or deliberate connection is documented. Corrosion monitoring channels should be distinguished from piezoresistive strain channels so that one signal is not incorrectly interpreted as the other.

F. Sulfate, Acid, Thermal, and Freeze–Thaw Exposure

No single durability test represents all environments. Sulfate attack depends on sulfate type, concentration, wetting, temperature, binder chemistry, and restraint. Acid dissolves cement phases and may destabilize carbonate healing products. High temperature can dehydrate hydrates, damage polymer shells, and reduce microbial viability. Freeze–thaw cycles generate hydraulic and osmotic stresses that can reopen cracks.

Exposure tests should reproduce the dominant field mechanism and include an appropriate comparator. Length change, mass, dynamic modulus, strength, microscopy, and transport may be combined. Accelerated concentration or temperature should be justified; extreme acceleration can produce a different mechanism and misleading ranking.

Healing performance is measured after, during, and where relevant before exposure. A seal formed in benign water may dissolve or crack in sulfate or freeze–thaw conditions. Conversely, certain mineral systems may remain effective. Repeated functional testing reveals whether the seal remains stable rather than merely forming once.

For hot climates and fire scenarios, carrier survival is a separate limit state. Encapsulation may protect spores during ordinary mixing and curing but not during fire. Post-fire healing research requires validated time–temperature histories, residual structural assessment, and evidence that any biological agent remains viable and safe.

G. Fracture Mechanics and Crack Geometry

Crack width at the surface is an incomplete descriptor. Crack depth, tortuosity, branching, roughness, and internal connectivity determine transport and the probability that a healing reservoir is intersected. A mechanically notched crack is repeatable but may differ from distributed shrinkage or flexural cracking. The creation method must match the research question.

Fracture energy and post-peak response can quantify changes caused by carriers, fibers, and interfaces. Displacement control allows a target crack mouth opening to be reached without uncontrolled failure. Digital image correlation maps localization, while X-ray computed tomography or sectioning can reveal internal geometry in selected specimens.

Healing can create bridging crystals that resist small reopening but fail under larger displacement. Refracture tests compare peak load, stiffness, fracture energy, and crack path. If the new crack diverts into adjacent matrix, apparent recovery may reflect a stronger filled interface; if it follows

the original plane, the measured bond directly reflects the healing product.

A design model should use the crack distribution expected from structural analysis and reinforcement detailing. The material system is then sized for that distribution. This linkage is essential for moving from coupon closure to an element-level probability of successful sealing.

H. Microbial Kinetics and Mass Transport

Microbial precipitation requires viable organisms, water, nutrient, a calcium source, carbonate generation, and space for crystals. Diffusion and advection supply reactants, while precipitation can progressively block pathways. Reaction rate can therefore decrease before a visible crack is completely filled. Temperature and pH affect both metabolism and mineral saturation.

A mechanistic model may couple water flow, solute transport, growth or activation, ureolysis or another metabolic rate, calcium–carbonate equilibrium, nucleation, and porosity change. Each added process creates parameters that need independent evidence. A simpler model with identifiable parameters can be more useful than an elaborate model calibrated to one curve.

Micro-scale experiments can measure urease activity, precipitation yield, and viability, but translation to concrete must include encapsulation, mixing, and transport. Comparing free cells, carrier-only control, killed-cell control, nutrient-only control, and full biological system helps separate microbial action from ordinary carbonate precipitation.

The engineering output remains functional: sealing rate and durability for a crack class. Biological measurements explain the mechanism and support safety, while hydraulic and structural measurements determine value to the asset.

I. Signal Processing and Damage Classification

Raw electrical time series contain drift, mains interference, switching transients, load-rate effects, temperature, and moisture response. Preprocessing may include synchronization, outlier flags, filtering, environmental compensation, and baseline normalization. Every transformation is documented because aggressive filtering can remove real crack events or manufacture smooth calibration.

Features may include resistance amplitude, loading and unloading slopes, hysteresis area, residual change, frequency-domain impedance terms, spatial channel ratios, and rate-dependent response. A physics-informed classifier combines these with load and environment. Training and validation cycles must be separated by specimen or batch to avoid leakage.

Detection performance is summarized by sensitivity, specificity, false alarms per time, localization error, and time to detection. Regression includes RMSE or interval coverage on blind loads. A high R^2 from repeated points on one specimen is not evidence that the system generalizes to another batch or moisture state.

The system should fail safely. If moisture or electrode health lies outside the calibrated domain, the output is “uncertain—inspect,” not a confident strain estimate. Human-readable reasons and raw data access support engineering judgment and regulatory acceptance.

J. Probabilistic Service-Life and Maintenance Optimization

Material properties, cover, exposure, crack occurrence, healing success, and threshold values are uncertain. Reliability analysis represents them as distributions with dependence where justified. Healing creates a state transition: an open crack may seal partially, remain stable, or reopen. Sensing changes the information state, not the physical resistance by itself.

A decision model can compare scheduled inspection, condition-based inspection, preventive repair, and no action. Costs include direct repair, access, traffic or service disruption, false alarm, missed deterioration, and consequence of failure. Carbon and resource use are tracked alongside money. The optimal policy can differ from the mixture with the longest mean initiation time.

Bayesian updating is appropriate when sensor or inspection evidence arrives. The prior deterioration distribution is updated with likelihood models calibrated from experiments. Poorly characterized sensors should produce modest updates; treating every signal as exact can create unjustified confidence.

Scenario communication should include percentile life, probability of intervention by a stated time, and the assumptions that dominate. A single “service life = 88 years” number hides uncertainty and may be mistaken for a guarantee.

K. Environmental Inventory and Uncertainty Propagation

Inventory data vary in age, geography, technology, allocation, and completeness. Cement may have plant-specific clinker factor and fuel mix; calcined clay may use different kilns; electricity changes by grid; transport depends on vehicle and load; biochar has multiple co-products. Each important factor needs a source and uncertainty range.

Monte Carlo analysis propagates input distributions through (3). Correlated variables should not be sampled independently when they share a cause, such as kiln efficiency and fuel use. Scenario uncertainty is separate from parameter uncertainty: whether a repair occurs is a scenario branch, while its material quantity may be a parameter distribution.

Results are checked for contribution and sensitivity. If a minor additive with a poorly known factor controls the conclusion, targeted supplier data are valuable. If clinker dominates every realization, precision effort should focus on cement composition rather than insignificant items.

Comparisons should report the probability that one candidate has lower GWP than another, not only overlapping error bars. A claimed advantage smaller than inventory uncertainty may still motivate research but is not a robust procurement distinction.

L. Costing, Procurement, and Supply Resilience

Laboratory ingredient prices do not represent production cost. Commercial evaluation includes raw materials, preprocessing, storage, dosing, quality control, rejected batches, curing, electrodes, acquisition hardware, software, training, and maintenance. Scale can reduce some costs but introduce certification and supply-chain requirements.

A resilient specification allows equivalent qualified sources while controlling critical performance. Reliance on a single specialty capsule or nanocarbon supplier can create delivery and price risk. Locally processed calcined clay and limestone may improve resilience, but their variability requires a capable quality system.

Procurement can request an alternate low-carbon baseline and separate options for healing and sensing. This reveals the incremental cost and value of each module. A bundled novelty price without decomposition prevents rational selection and future competition.

Payment and acceptance milestones align with evidence: constituent approval, trial batch, full-scale mock-up, commissioning, and seasonal performance. Warranty language should reflect measurable functions and realistic uncertainty rather than an undefined promise that concrete “heals itself.”

M. Industrial Scale-Up and Manufacturing Readiness

Scale-up changes shear, residence time, temperature, dosing accuracy, and material logistics. Powders that disperse in a laboratory planetary mixer may form balls in a drum mixer; capsules that survive hand mixing may rupture under pumping; biochar moisture may change during storage. Production trials are a distinct research phase.

A process flow diagram identifies storage, feeding, preconditioning, conductive-slurry preparation, capsule addition, mixing, transport, placement, curing, electrodes, and data commissioning. Hazard review addresses dust, biological materials, high-pressure CO₂, and electrical equipment. Each control has an owner and record.

Statistical process control uses rapid proxies linked to final performance. Examples include clay reactivity, slurry resistivity, fresh density and air, mixer power, hardened resistivity coefficient of variation, and early strength. Proxy limits are established from correlated trial data, not selected for convenience.

Manufacturing readiness is achieved when the process repeatedly meets specifications with ordinary operators and planned maintenance. A single expert-supervised successful pour is a demonstration, not a stable production process.

N. Regionalization for Jaipur and Wider India

Regional design starts with climate, exposure, material supply, energy, transport, workmanship, and applicable standards. Jaipur’s hot and seasonally dry conditions can accelerate slump loss and evaporation while providing limited moisture for healing outside monsoon periods. Precast curing or deliberate wet–dry activation may be more reliable than passive outdoor exposure.

Calcined-clay feasibility depends on actual deposits, mineralogy, competing uses, and logistics. Limestone and cement are widely available, but a local LC3 supply chain needs consistent processing and quality control. Environmental factors should reflect Indian fuels and electricity rather than imported generic databases.

Priority research can use locally relevant water quality, temperature cycles, dust, and wet–dry exposure. Coastal chloride studies remain necessary for national infrastructure but should not substitute for hot-dry carbonation, shrinkage, and water-retaining applications relevant to Rajasthan.

University–industry pilots can begin with noncritical precast products that offer repeatability and inspection. Open methods and datasets build local capability and allow students, laboratories, producers, and authorities to compare results using common protocols.

O. Research Integrity, Authorship, and Publication Readiness

A professional paper distinguishes measured data, literature values, model assumptions, and illustrative results. The present manuscript labels the scenario outputs explicitly because no laboratory campaign is claimed. A future experimental version should replace scenario tables with traceable measurements and revise the abstract, methods, results, and conclusions accordingly.

Authorship reflects substantial intellectual and practical contribution. Constituent suppliers or sponsors are acknowledged and conflicts disclosed. Negative results, failed batches, deviations, and excluded specimens are documented. Image processing retains original files and avoids selective fields that overstate closure.

References are verified against the cited claim, and standards are identified by the version actually used. Numerical precision matches uncertainty. Equations define every variable and unit. Data and code availability statements identify access conditions. Ethical and biosafety approvals are stated where biological work requires them.

These practices are not administrative decoration. They are part of engineering safety: transparent provenance allows another group to reproduce, challenge, and improve the material before it is used in infrastructure.

APPENDIX H — ILLUSTRATIVE FIELD DEMONSTRATION PLAN

A. Demonstrator Definition

An appropriate first field demonstrator is a set of non-prestressed precast drainage or utility-chamber panels produced in one controlled plant. The panels experience wet-dry cycling and visible service cracking but can be isolated and replaced if necessary. Four material groups are included: OPC control, LC3 baseline, LC3 with healing, and LC3 with healing plus sensing. Identical geometry, reinforcement, cover, and curing enable a functional comparison without relying on the novel modules for primary structural safety.

The pilot question is stated before production: Does the LC3 matrix reduce verified cradle-to-gate GWP while meeting strength and transport requirements; does the healing module improve sealing of naturally or deliberately generated service-width cracks; and does the sensing module detect crack events after environmental compensation with an acceptable false-alarm rate? Success thresholds and analysis methods are registered in the pilot protocol.

B. Production and Commissioning

Three production lots are scheduled on different days to expose normal plant variability. Constituent lots, moisture, temperature, mixer power, flow, density, air, capsule addition time, conductive-slurry resistance, and curing are recorded. Companion cylinders, prisms, and transport specimens are made from each lot. At least one full-scale panel from every lot undergoes proof loading to a predefined service crack width, followed by unloading and documented healing conditioning.

Sensing panels contain redundant four-probe paths across predicted crack zones and reference paths away from those zones. Temperature and relative-humidity sensors are colocated. Commissioning records zero-load baselines, proof-load response, unload residual, and repeat cycles. Channel

health, cable protection, acquisition enclosure, timestamps, and backup are accepted before the panel enters service.

C. Monitoring and Intervention

During the first year, data are reviewed monthly and after heavy rainfall, unusual loading, or a threshold event. Visual crack maps and standardized photographs are collected at commissioning and at 1, 3, 6, and 12 months. Where access permits, localized water-flow or absorption measurements are repeated. A sensor Level 1 event prompts data review; Level 2 prompts field inspection; and Level 3 requires an engineer to assess service restriction or repair. Autonomous healing never cancels a safety response.

Environmental compensation is recalibrated only using low-load intervals and is version controlled. The pilot report distinguishes real structural events, environmental excursions, sensor-health faults, and unexplained anomalies. If a crack visually closes, functional sealing is checked before it is recorded as healed. If electrical response returns toward baseline but leakage persists, the event is not counted as successful functional recovery.

D. Carbon and Cost Verification

Plant-specific environmental data are collected for the cementitious components, transport, electricity, curing, healing material, conductive addition, electrodes, and rejected units. Declared storage is credited only when measured by the agreed method. The same functional unit and allocation rules are applied to all groups. Initial cost is separated into base concrete, low-carbon binder, healing, sensing hardware, data service, and additional quality assurance so that later projects can select modules independently.

At 12 months, the project publishes measured production variability, embodied carbon with uncertainty, strength and transport results, crack-width histories, sealing recovery, sensor performance, false alarms, maintenance actions, and deviations. A decision panel then recommends rejection, reformulation, a second-season pilot, or limited application. Scaling requires evidence that ordinary plant staff can reproduce the process and that the monitoring result changes a real inspection or maintenance decision.

APPENDIX I — PRACTICAL DESIGN REVIEW CHECKPOINTS

A. Concept Review

At concept stage, the engineer identifies the asset function, exposure, design life, inspection access, likely crack mechanisms, consequence of leakage or corrosion, and current maintenance burden. The review asks whether a lower-clinker conventional concrete can already satisfy the need. Healing is considered only when a defined crack-related service problem remains, and sensing is considered only when information can trigger a funded decision. This avoids adding complexity without asset value.

The concept record states mandatory thresholds and preferred objectives. Strength, stability, fire resistance, and exposure-specific durability remain mandatory. Carbon, cost, repair disruption, healing, and monitoring value are optimized within those limits. The project selects a functional unit and comparator before environmental calculations begin so that a later attractive result cannot be produced by changing the boundary.

B. Detailed Material Review

The detailed review examines constituent sources, variability, compatibility, safety, storage, and dosing. Absolute-volume closure and effective-water corrections are independently checked. The base LC3 mixture is validated before healing and sensing modules are introduced. Each module has an identified mechanism, target dosage window, process requirement, acceptance test, and fallback. Interactions are investigated using planned factorial contrasts rather than informal recipe changes.

The review also confirms that analytical methods can distinguish the claimed mechanisms. Mineral precipitation is identified chemically; viable microbial action is separated from autogenous healing; electrical response is separated from temperature and moisture; and carbon storage is measured separately from supplied gas or total biochar mass. Samples and raw data are retained for independent review.

C. Structural and Durability Review

Structural calculations use code-compliant material properties and do not credit healing for load capacity unless repeated, statistically supported recovery is demonstrated for the relevant stress state. Crack-width control is designed by reinforcement, fibers, section geometry, restraint management, and construction practice. The healing system is then evaluated against the residual crack distribution. Printed elements include anisotropic properties and interface limits explicitly.

Durability review maps each exposure to a mechanism and test. Chloride, carbonation, sulfate, freeze–thaw, abrasion, leaching, temperature, and wet–dry effects are not represented by one universal index. Cracked and healed specimens are included where cracks govern. Service-life modeling uses calibrated transport and uncertainty, and field inspection remains part of the defense-in-depth strategy.

D. Production Readiness Review

Before full production, a mock-up demonstrates material receipt, moisture correction, carbon dispersion, capsule addition, mixing, transport, placement or printing, curing, electrode installation, and data commissioning. Ordinary production personnel follow controlled instructions. Deviations, cleanout requirements, dust and biological controls, CO₂ handling, rejected material, and emergency stops are rehearsed. Rapid quality indicators are linked to final performance through trial data.

The readiness decision requires repeatability across independent lots. Averages alone are insufficient when one lot fails. Control limits, hold points, responsibilities, and corrective actions are written into the inspection plan. A conventional approved mixture remains available if the multifunctional process falls outside its validated window; schedule pressure is not allowed to override material acceptance.

E. Handover and Long-Term Review

Handover transfers the material passport, as-built sensor map, calibration, raw baseline, software version, thresholds, inspection plan, spare hardware, access rights, and response responsibilities to the asset owner. Staff are trained to distinguish sensor health, environmental drift, and possible damage. Data retention and cybersecurity match the asset's consequence class. Electronics renewal is budgeted independently from concrete service life.

Long-term review compares predicted and observed behavior. Crack events, healing, leakage, corrosion indicators,

alarms, inspections, repairs, costs, carbon, and operational disruption update the reliability model. If monitoring does not change decisions or healing does not recover the specified function, future projects remove or redesign the module. Continuous learning—not an irreversible commitment to novelty—is the defining feature of responsible deployment.

ACKNOWLEDGMENT

The author acknowledges the global research community advancing low-carbon binders, self-healing cementitious materials, additive construction, structural health monitoring, and transparent life-cycle assessment. No external funding or experimental dataset is claimed for the illustrative scenario analysis presented in this manuscript.

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