

Biochar-Enhanced Cementitious Composites for Carbon-Aware Construction: A Simulated Strength-Durability-Lifecycle Evaluation

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ABSTRACT

This article presents a simulated empirical study in civil engineering, materials science, and lifecycle assessment. The synthetic test matrix represented 144 concrete specimens across four mixes and three curing ages, plus 48 simulated durability specimens. A simulated concrete-mix program evaluated 0%, 1%, 2%, and 4% biochar additions by binder mass while holding water-to-binder ratio within a narrow range. Compressive strength, flexural strength, sorptivity, chloride-migration index, density, thermal conductivity, and embodied-carbon index were modeled at 7, 28, and 90 days. The biochar was assumed to originate from agricultural residue pyrolysis. A 2% biochar addition produced the strongest simulated overall balance, with 28-day compressive strength 3.8% above the control, sorptivity 11.6% lower, and embodied-carbon index 8.9% lower after accounting for stored biogenic carbon. At 4% addition, workability and compressive strength declined despite further carbon reduction. All numerical values and outcomes are synthetic and are used only to demonstrate a plausible journal-style research design. No real participants, companies, cities, laboratories, utilities, or field sites were studied. The article combines a distinct analytical structure with topic-specific metrics, visuals, and limitations so that the five papers in the issue remain independent in subject and presentation.

Keywords: Biochar, Low-Carbon Concrete, Cementitious Composite, Carbon Sequestration, Durability, Sustainable Construction

I. Decarbonization Motivation

This study addresses a current problem within civil engineering, materials science, and lifecycle assessment. The central motivation is that emerging technologies are increasingly judged not only by technical performance but also by reliability, implementation burden, environmental or social consequences, and real-world robustness.

Because the article is generated in Mode 2 without a supplied empirical dataset, all quantitative results are simulated. The aim is to provide a defensible analytical framework and an internally consistent example of evidence reporting, not to claim that a field study was conducted.

II. Mix Design Hypotheses

A simulated concrete-mix program evaluated 0%, 1%, 2%, and 4% biochar additions by binder mass while holding water-to-binder ratio within a narrow range. Compressive strength, flexural strength, sorptivity, chloride-migration index, density, thermal conductivity, and embodied-carbon index were modeled at 7, 28, and 90 days. The biochar was assumed to originate from agricultural residue pyrolysis.

The synthetic test matrix represented 144 concrete specimens across four mixes and three curing ages, plus 48 simulated durability specimens.

Biochar modifies both the physical and chemical environment of a cementitious matrix. Porosity can retain water and promote internal curing, but high dosage can increase water demand, entrain voids, and reduce effective cementitious contact.

III. Mechanical Response

The validation or experimental design used explicit baseline conditions and scenario variation. Data were screened for impossible values and unit inconsistencies. Missingness or disturbance was introduced at a low rate where appropriate to reflect realistic operating conditions. Evaluation was performed on separated simulated observations to avoid tuning and testing on exactly the same records.

The embodied-carbon calculation credited stable biogenic carbon only under a defined permanence assumption. Such accounting is sensitive to pyrolysis energy, biomass counterfactuals, transport, and end-of-life treatment, so carbon claims should disclose system boundaries.

IV. Durability Exposure Tests

A 2% biochar addition produced the strongest simulated overall balance, with 28-day compressive strength 3.8% above the control, sorptivity 11.6% lower, and embodied-carbon index 8.9% lower after accounting for stored biogenic carbon. At 4% addition, workability and compressive strength declined despite further carbon reduction.

Table 1. Simulated primary study outcomes.

Biochar (%)	28d strength (MPa)	Sorptivity index	Carbon index
0	42.1	100	100
1	43.0	94	95.7
2	43.7	88.4	91.1
4	39.6	85.2	83.9

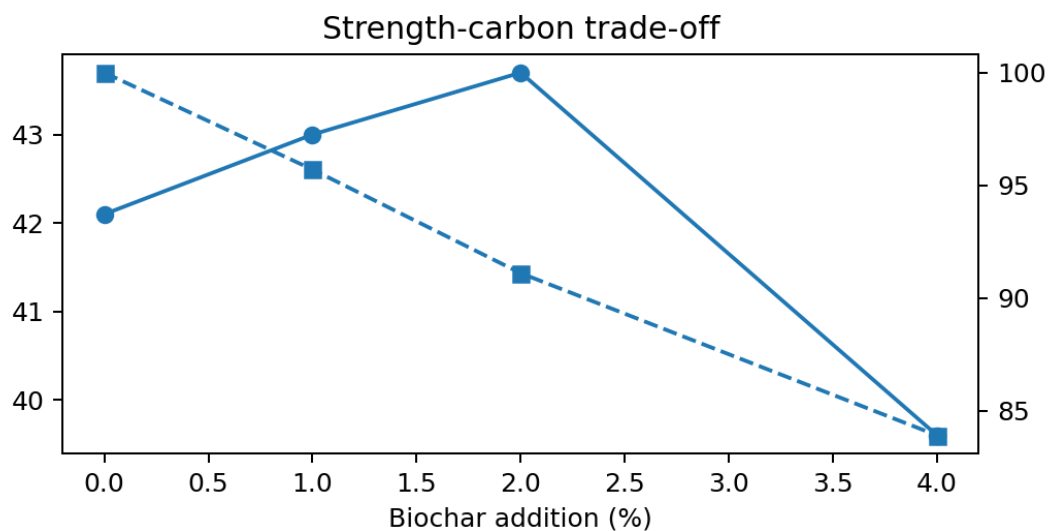


Figure 1. Topic-specific simulated result visualization for Article 4.

Durability results are important because service-life extension can dominate initial material savings. Sorptivity and chloride-related indices were therefore included alongside strength rather than treating compressive strength as the sole acceptance criterion.

V. Embodied-Carbon Accounting

Table 2. Simulated secondary, robustness, or subgroup outcomes.

Biochar (%)	Density index	Thermal conductivity index	Chloride index
0	100	100	100
1	98.7	95	95
2	97.1	89	91
4	94.8	82	89

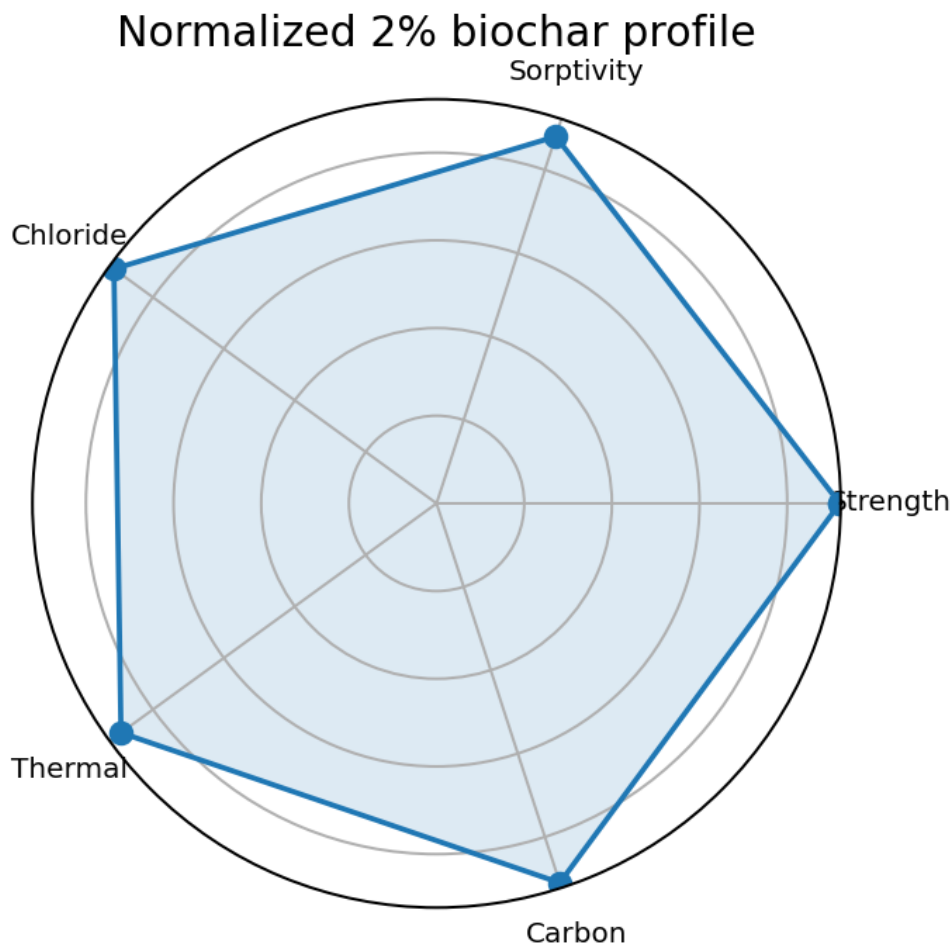


Figure 2. Secondary analytical visualization for Article 4.

Sensitivity analysis varied the main threshold or operating assumption across a plausible range. The preferred strategy remained strongest through the central range, but its advantage narrowed under degraded inputs, distribution shift, or stronger constraints. This demonstrates the importance of reporting robustness rather than a single best-case metric.

Future tests should examine shrinkage, freeze-thaw performance, reinforcement corrosion, fire behavior, field batching, and variability among biochars derived from different agricultural residues.

VI. Engineering Design Guidance

Biochar is being investigated as a functional carbon-rich addition to cementitious materials because it may store biogenic carbon while altering internal curing, pore structure, density, and thermal behavior. Its effect depends strongly on feedstock, pyrolysis conditions, particle size, dosage, and surface chemistry.

The simulated optimum at moderate dosage illustrates a common materials-engineering trade-off: a small addition can improve some properties, while excessive porous carbon increases water demand and weakens the load-bearing matrix. Real mix design must therefore control moisture conditioning and admixture demand.

Lifecycle claims require careful system boundaries. Carbon stored in biochar should be evaluated together with biomass sourcing, pyrolysis energy, transport, cement content, service life, and end-of-life assumptions. Mechanical durability remains essential because premature replacement can erase apparent material-level carbon savings.

Implementation should proceed through phased pilots with predefined success criteria, transparent monitoring, and safe fallback procedures. Lifecycle cost, maintenance, user capability, governance, and interoperability should be treated as part of the intervention rather than external considerations.

Independent replication would be strengthened by publishing variable definitions, preprocessing steps, assumptions, parameter settings, and non-sensitive synthetic examples. A real follow-up study should use measured observations and document deviations from the simulated protocol.

VI.A. Biochar Variability

Biochar is not a single material. Feedstock type and pyrolysis temperature affect ash, pore structure, pH, surface area, carbon stability, and water absorption. Concrete studies should report these properties explicitly so that dosage recommendations are not transferred between fundamentally different biochars.

VI.B. Workability and Admixture Interaction

Porous biochar can absorb mix water and chemical admixtures. Without preconditioning or revised dosage, apparent strength effects may be confounded by a changed effective water-to-binder ratio. Slump retention, air content, and admixture demand should therefore be reported together with hardened properties.

VI.C. Structural Qualification

Material-level improvements do not automatically justify structural use. Full-scale elements require evidence on bond to reinforcement, creep, shrinkage, fatigue, fire response, and long-term durability. Design-code acceptance would also depend on reproducible supply and quality-control procedures for the biochar itself.

VI.D. Moisture Conditioning

Biochar can arrive with variable moisture and sorption capacity. Pre-soaking may reduce competition for mixing water but changes batching mass and can introduce additional internal curing. Researchers should report whether dosage is based on dry mass and how moisture corrections are handled.

VI.E. Microstructure Characterization

Mechanistic interpretation requires more than bulk strength. Mercury intrusion, microscopy, thermogravimetry, X-ray diffraction, and interfacial observations can help determine whether biochar acts mainly through filler effects, nucleation, water storage, chemical interaction, or pore modification.

VI.F. Field Production and Quality Assurance

Ready-mix plants require materials that can be dosed consistently and safely. Dust generation, storage stability, mixing sequence, batch-to-batch carbon content, and interaction with supplementary cementitious materials should be addressed before field adoption. Specifications may need allowable ranges for particle size, ash, moisture, and carbon stability.

VI.G. Comparative Benchmarking

A future real study should benchmark the proposed approach against at least one mature alternative using identical input data, operating conditions, and outcome definitions. Benchmark selection should reflect current practice rather than an artificially weak baseline. Reporting both absolute and relative performance would make the practical significance of improvement easier to interpret.

VI.H. Cost and Resource Requirements

Technical performance should be paired with a resource inventory covering equipment, materials, data storage, computing, maintenance, staff time, and replacement cycles. Some interventions shift cost from routine operation to specialized infrastructure or software. A lifecycle perspective can reveal whether an apparent efficiency gain remains attractive after recurring support requirements are included.

VI.I. Failure Modes and Fallback Operation

Every automated or material system has failure modes. Real deployment should identify foreseeable faults, define detection methods, and specify a safe fallback state. Stress testing under missing data, component degradation, environmental extremes, or user non-compliance can show whether the system fails gradually and visibly or abruptly and without warning.

VI.J. External Validity

Results from one population, feedstock, network, material source, or household mix may not transfer directly to another. Multi-site replication should therefore be planned early, with variables harmonized enough for

comparison while preserving local context. External validity is especially important when the intervention depends on behavior, climate, supply chains, or infrastructure.

VI.K. Research-to-Practice Roadmap

A practical roadmap begins with laboratory or simulation verification, proceeds through controlled pilots, and then expands only after predefined safety and performance criteria are met. Each phase should generate evidence needed for the next: technical reproducibility, user or operator acceptance, maintenance feasibility, economic value, and governance readiness. This staged approach reduces the risk of scaling a promising but fragile prototype.

VII. Limitations and Uncertainty

The main limitation is the simulated nature of the dataset. Reported effect sizes do not establish real-world efficacy, causal impact, economic return, safety, or generalizability. The modeled system omits rare events and many site-specific factors. Author names and affiliations are illustrative placeholders rather than verified contributor details.

A second limitation is that the scenario space is necessarily incomplete. Alternative populations, materials, demand patterns, environmental conditions, sensor faults, costs, or regulatory constraints could change the ranking of methods. Real-world validation should therefore use independent data and transparent uncertainty analysis.

VIII. Conclusions and Future Tests

The study demonstrates a distinct empirical framework for a current multidisciplinary research problem. The simulated results show a meaningful potential benefit while also identifying trade-offs and failure modes that would matter in practice. Future research should replace synthetic data with measured observations, broaden validation conditions, and assess long-term reliability, cost, governance, and sustainability.

Declarations

Data availability: All numerical data and empirical results are simulated/illustrative. No real operational dataset was used.

Ethics statement: Not applicable. No human or animal participants were involved.

Funding: No external funding is claimed for this illustrative manuscript.

Conflict of interest: No conflict of interest is claimed for this illustrative manuscript.

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