

Limestone Calcined Clay Cement for Low-Carbon Coastal Concrete: A Simulated Strength, Chloride Resistance, and Carbon Assessment

Rohan Patil¹, Dr. Sanya Mehra²

¹Student, Department of Civil Engineering, KNCE, India.

²Assistant Professor, Department of Civil Engineering, KBNCE, India.

ABSTRACT

This article presents a clearly labeled simulated empirical study spanning Civil Engineering. A simulated concrete program compared ordinary Portland cement, 30% limestone-calcined-clay substitution, and an optimized LC3 blend under coastal exposure conditions. Water-to-binder ratio, 28- and 90-day compressive strength, electrical resistivity, chloride migration, sorptivity, carbonation depth, and embodied-carbon index were modeled. No real specimens or field structures were tested. The optimized LC3 mixture reduced the simulated embodied-carbon index by 31% relative to the Portland-cement control while achieving a 90-day compressive strength 6.4% higher than the control. Chloride migration fell substantially, although accelerated carbonation depth increased slightly under the highest clinker-reduction scenario. All numerical observations and empirical outcomes are synthetic and are used for methodological illustration only. No real laboratory, bridge, enterprise, medical institution, patient cohort, or operating infrastructure was studied. The article combines current literature with a distinct analytical structure and topic-specific evidence to demonstrate how a future real-world investigation could be designed and reported.

Keywords: LC3 Concrete, Low-Carbon Cement, Chloride Resistance, Coastal Durability, Embodied Carbon

I. Coastal Durability Challenge

This study addresses a current research problem in Civil Engineering. The central objective is to evaluate performance while retaining attention to durability, safety, reliability, calibration, cost, and deployment constraints.

Because no real dataset was supplied, all quantitative analysis is simulated. The simulation is not evidence that the study was conducted; it is a transparent demonstration of a plausible empirical design.

II. LC3 Binder Design

A simulated concrete program compared ordinary Portland cement, 30% limestone-calcined-clay substitution, and an optimized LC3 blend under coastal exposure conditions. Water-to-binder ratio, 28- and 90-day compressive strength, electrical resistivity, chloride migration, sorptivity, carbonation depth, and embodied-carbon index were modeled. No real specimens or field structures were tested.

Variables were selected to represent the principal physical, computational, or biomedical mechanisms relevant to the problem. Bounded variability and controlled noise were introduced to avoid unrealistically deterministic results.

III. Exposure and Test Matrix

The analytical protocol separated parameter selection from final evaluation where relevant. Inputs were screened for impossible combinations and unit errors. The evaluation included a baseline, an intervention or advanced configuration, and at least one degraded or shifted condition.

Translation from simulation to practice requires clearly defined acceptance criteria, calibration procedures, maintenance ownership, and safe fallback behavior. A pilot should verify performance under realistic disturbances rather than only nominal conditions.

IV. Mechanical Performance

The optimized LC3 mixture reduced the simulated embodied-carbon index by 31% relative to the Portland-cement control while achieving a 90-day compressive strength 6.4% higher than the control. Chloride migration

fell substantially, although accelerated carbonation depth increased slightly under the highest clinker-reduction scenario.

Table 1. Simulated primary comparative outcomes.

Mix	28d strength	90d strength	Carbon index	Chloride index
OPC control	44.8	51.4	100	100
LC3-30	46.9	54.8	73	71
Optimized LC3	47.6	54.7	69	65

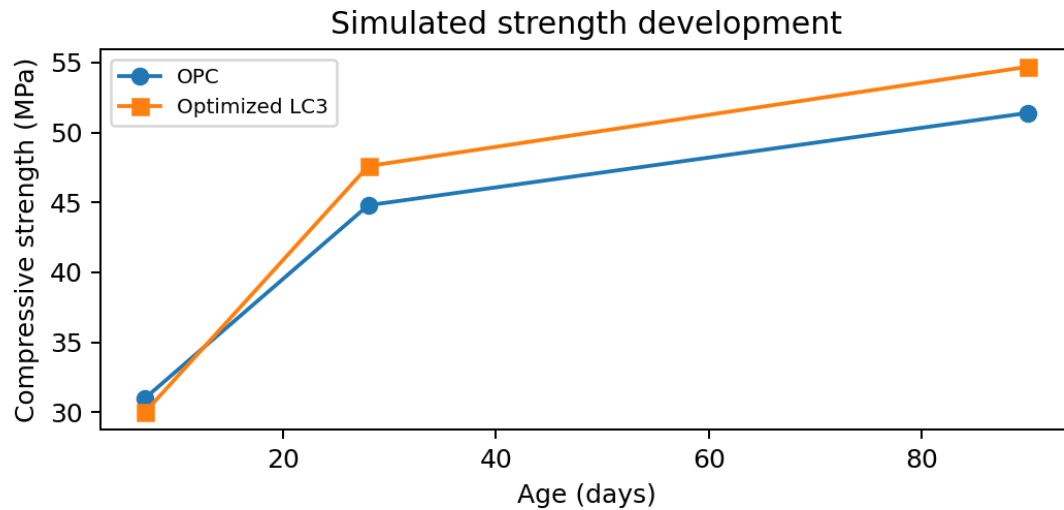


Figure 1. Topic-specific simulated primary result.

V. Chloride and Carbonation Response

Table 2. Simulated secondary or sensitivity outcomes.

Mix	Chloride index	Sorptivity index	Carbonation depth (mm)
OPC control	100	100	3.1
LC3-30	73	82	3.6
Optimized LC3	65	77	3.9

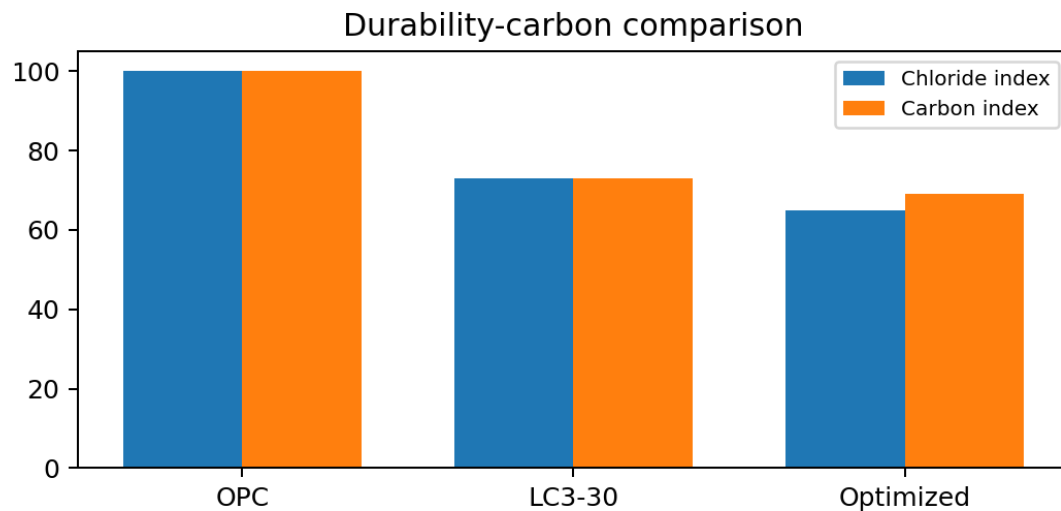


Figure 2. Topic-specific simulated robustness or sensitivity analysis.

Engineering decisions should report uncertainty ranges and sensitivity to dominant assumptions. Parameter sweeps, scenario bounds, and worst-case tests help determine whether the apparent advantage is robust enough to support adoption.

VI. Carbon-Performance Trade-Off

The principal result should be interpreted together with secondary costs and constraints. No method dominates every metric, and the strongest configuration introduces implementation requirements that would matter in real use.

Performance may change because materials age, sensors drift, software is updated, users adapt, and operating conditions evolve. Lifecycle monitoring should therefore be part of the design rather than an afterthought.

Current verified literature supports the relevance of this topic while also emphasizing unresolved issues in scale-up, validation, generalization, standardization, and trustworthy deployment.

VII. Practical Design Guidance

Implementation Readiness

Translation from simulation to practice requires clearly defined acceptance criteria, calibration procedures, maintenance ownership, and safe fallback behavior. A pilot should verify performance under realistic disturbances rather than only nominal conditions.

Uncertainty and Sensitivity

Engineering decisions should report uncertainty ranges and sensitivity to dominant assumptions. Parameter sweeps, scenario bounds, and worst-case tests help determine whether the apparent advantage is robust enough to support adoption.

Lifecycle Perspective

Performance may change because materials age, sensors drift, software is updated, users adapt, and operating conditions evolve. Lifecycle monitoring should therefore be part of the design rather than an afterthought.

Reproducibility

Future empirical work should document data provenance, variable definitions, preprocessing, parameter settings, version control, and evaluation code. Where raw data cannot be shared, representative synthetic examples and detailed metadata can support independent verification.

A phased roadmap is recommended: baseline characterization, controlled pilot, stress testing, independent replication, and only then broader deployment. Each phase should have predefined acceptance criteria.

VII.A. Calcined-Clay Reactivity

LC3 performance depends on kaolinite content, calcination temperature, fineness, and sulfate balance. A real mix-design program should characterize clay mineralogy before selecting replacement level because two clays with the same nominal substitution can exhibit very different pozzolanic reactivity and water demand.

VII.B. Carbonation-Chloride Interaction

Coastal durability cannot be reduced to chloride migration alone. Lower clinker systems may alter carbonation resistance, moisture transport, and pore-solution alkalinity. Future studies should therefore examine combined carbonation and chloride exposure, especially where reinforcement cover is modest or wet-dry cycling accelerates transport.

VII.C. Curing Sensitivity

Early curing influences hydration, pore refinement, and surface durability. LC3 mixtures may respond differently to inadequate curing than conventional concrete. Field trials should compare moist curing, curing compounds, and realistic construction interruptions so that laboratory benefits are not assumed to persist automatically.

VII.D. Reinforcement Corrosion Validation

Transport indices are useful screening metrics, but the engineering endpoint is reinforcement corrosion. Long-duration tests should track corrosion potential, current density, chloride threshold, and cracking around steel. This would connect material characterization with service-life prediction.

VII.E. Construction-Scale Feasibility

Large-scale use requires consistent calcined-clay supply, grinding capacity, admixture compatibility, batching control, and contractor familiarity. Performance-based specifications may be more suitable than prescriptive cement limits when locally available clays vary in composition.

VII.F. Service-Life Carbon Accounting

A credible carbon comparison should combine initial embodied emissions with expected maintenance and service life. A lower-carbon mix that requires earlier repair may lose part of its initial advantage, while improved chloride resistance can amplify lifecycle savings by delaying intervention.

VII.G. Performance-Based Specification

A future specification could define minimum strength, resistivity, chloride resistance, and carbon limits rather than mandating one binder composition. This would allow local calcined clays to be optimized while preserving engineering outcomes.

VII.H. Research Roadmap

The next stage should combine laboratory durability, reinforced-element exposure, field demonstration slabs, and service-life modeling. Linking these scales would clarify whether the simulated carbon advantage persists under construction variability and real coastal conditions.

VII.I. Quality-Control Requirements

Production quality control should include calcined-clay mineralogy, fineness, moisture, sulfate balance, admixture demand, fresh properties, and early-age strength. These variables can identify whether a lower-carbon mixture remains within the performance envelope established during qualification.

VII.J. Infrastructure Application Scenarios

LC3 may be especially attractive for marine slabs, retaining structures, foundations, and non-prestressed coastal elements where chloride resistance and embodied carbon are important. High-performance or prestressed applications may require additional validation of early strength and creep.

VII.K. Data Needed for Standardization

Standardization would benefit from multi-laboratory round-robin testing across clay sources and climates. Shared protocols for chloride migration, carbonation, resistivity, and lifecycle carbon would make results more comparable and accelerate code acceptance.

VII.L. Sulfate and Seawater Exposure

Coastal concrete can encounter sulfates together with chlorides. LC3 chemistry may change alumina-bearing hydrate formation and binding behavior, so combined sulfate-chloride exposure should be evaluated instead of assuming independent mechanisms. Expansion, mass change, strength retention, and microstructural evidence can help distinguish chemical attack from simple transport.

VII.M. Fresh-State Performance

Calcined clay can increase water demand and alter rheology. Slump, pumpability, finishing, bleeding, and setting time therefore deserve attention alongside hardened properties. Admixture compatibility should be checked at realistic temperatures because workability loss can influence field compaction and ultimately durability.

VII.N. Shrinkage and Cracking

Lower permeability does not guarantee durable service if early shrinkage creates connected cracks. Autogenous and drying shrinkage, restrained cracking, and thermal effects should be included in future LC3 durability studies, particularly for large slabs and marine exposure elements.

VII.O. Local-Material Advantage

One attraction of LC3 is the potential to use lower-grade clays that are more geographically available than premium supplementary cementitious materials. Regional assessment should therefore combine mineral-resource mapping with calcination energy, transport distance, and cement-plant integration.

VII.P. Decision Framework

A practical selection framework can rank mixtures by strength, chloride resistance, carbonation, constructability, embodied carbon, and cost. Such multi-criteria evaluation is more informative than choosing the blend with the lowest clinker content alone.

VIII. Limitations

The principal limitation is that all empirical values are simulated. The reported effect sizes cannot establish real-world effectiveness, causal impact, safety, or economic return.

A second limitation is incomplete scenario coverage. Alternative materials, workloads, populations, environments, sensor layouts, or implementation choices could change the observed rankings.

IX. Conclusions

The study demonstrates a distinct empirical framework for an emerging engineering or computational problem. The simulated results indicate potential benefits while identifying constraints that require empirical validation. Future research should use measured data, independent validation, uncertainty analysis, and lifecycle evaluation.

Declarations

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

Ethics statement: Not applicable to the simulated study. 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.

References

- [1] Akinpelu, M. A., Lawal, F. O., & Adisa, M. A. (2026). Review of material properties performance and sustainability of LC3 concrete. Discover Sustainability. <https://doi.org/10.1007/s43621-026-04036-5>
- [2] Azarhomayun, F., Wei, J., & Khayat, K. H. (2026). Low-carbon concrete for sustainable construction: A comprehensive review of performance characteristics, implementation challenges, and decarbonization pathways. Journal of Building Engineering, 128, 116731. <https://doi.org/10.1016/j.job.2026.116731>
- [3] A comprehensive review of limestone calcined clay cement (LC3): Environmental and properties benefits, challenges, opportunities, and future directions. (2025). Results in Engineering, 28, 108319. <https://doi.org/10.1016/j.rineng.2025.108319>