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A Theoretical Model for Carbon-Neutral Concrete Mix Design Considering Diverse Curing Conditions

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Abstract

The greening of concrete is a critical research focus in civil engineering, driven by the increasing global demand for aggregates, the worldwide enforcement of decarbonization policies, and the urgent challenge of climate change. As one of the largest energy consumers and CO2 producers, the cement and concrete industry must align structural efficiency with ambitious sustainability targets. This paper develops a conceptual theoretical model

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within a numerical framework, based on first principles, to analyze the impact of various curing conditions on the environmental-structural performance of carbon-neutral concrete mix designs. The model is built upon three intertwined pillars: (1) an Environmental Pillar focused on reducing Portland cement content via green substitutes like fly ash and slag, using embodied carbon as a key metric; (2) a Mechanical Pillar ensuring engineering performance (strength, durability) through optimized mix proportions; and (3) a Curing Conditions Pillar that accounts for the effects of different curing methods (e.g., wet, steam, CO2) on carbon performance and long-term structural response. This integrated approach allows for the study of complex interactions between environmental, technical, and structural factors. The model provides a foundation for future computational simulations and the development of standardized performance metrics for sustainable construction codes, offering a practical framework for engineers, scholars, and policymakers to advance toward carbon-neutral concrete.

Keywords: Carbon-Neutral Concrete, Sustainable Mix Design, Curing Optimization, Supplementary Cementitious Materials, Embodied Carbon Reduction, Life Cycle Assessment, CO_2 Mineralization, Geopolymer Concrete, Theoretical Modeling, Infrastructure Sustainability.

Introduction

Concrete is the most widely used building material on earth, forming the foundation of global infrastructure. However, the production of its primary binder, Portland cement, is a significant source of global CO2 emissions, accounting for an estimated 7–8% of the total [1]. This environmental impact has made the development of low- or zero-carbon concrete a paramount challenge for scientists and engineers. Consequently, novel mix design methodologies aimed at minimizing the embodied carbon of concrete without

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compromising its structural performance are under intensive investigation 2 . The pursuit of carbon neutrality in concrete influences sustainable urbanization, infrastructure resilience, and compliance with international climate agreements like the Paris Accord. As the construction industry faces increasing pressure to provide sustainable solutions, environmental factors are becoming integral to commercial design processes. Theoretical models that integrate material advances (e.g., supplementary cementitious materials, SCMs) with technological ones (e.g., optimized curing regimes) are essential for envisioning a sustainable future for concrete 3 . This review addresses a less-researched dimension of sustainable concrete: the role of curing conditions in achieving carbon neutrality. While material substitution has been widely studied, curing regimens critically govern hydration kinetics, strength development, and durability, thereby influencing the material's ultimate carbon footprint. Traditional methods like water or steam curing can have divergent carbon impacts based on their energy intensity and interaction with alternative binders. A systematic study of curing regimes within carbon-neutral mix design is therefore both scientifically justified and practically necessary 4 . This paper establishes a foundation for integrating curing protocols into the design of carbon-neutral concretes. Through a structured review spanning environmental, mechanical, and technological disciplines, it presents a knowledge overview, identifies research gaps, and conceptualizes a framework for assessing the carbon impact of curing regimes. The objective is not only to collate current knowledge but also to outline a trajectory for future research in green concrete technology 5 . A systematic investigation of the literature was performed, drawing from journals, conference proceedings, and technical reports. Renowned databases such as Scopus, Web of Science, Science Direct, and the ASCE Library were searched, with a focus on publications from the last two decades to thoroughly evaluate this rapidly

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evolving field. This methodology ensures the conceptual framework is grounded in international best practices 6 .

THEORETICAL FRAMEWORK

Key Terms

The concept of carbon-neutral concrete is part of a larger trend toward sustainable construction. A carbon-neutral concrete mix is defined not as a "zero emissions" mix, but as one that balances CO_2 emissions from production, transportation, and hardening with savings from alternative binders, recycling, or carbon capture 7 .

Curing involves maintaining adequate temperature and humidity to ensure sufficient cement hydration. Different methods (e.g., water curing, steam curing, ambient curing, CO_2 curing) significantly impact the concrete's mechanical properties and embodied carbon. For instance, steam curing accelerates strength development but requires high energy input, while ambient curing, though low-energy, may compromise durability if not properly managed 8 .

Supplementary Cementitious Materials (SCMs), such as fly ash, slag, and silica fume, are used to partially substitute Portland cement, reducing the mix's carbon intensity. The interaction between SCMs and curing conditions is complex, as their pozzolanic reactions are highly dependent on ambient humidity and temperature 9 .

Theoretical Models and Historical Context

Several theoretical models describe and predict the performance of sustainable concretes:

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- Hydration Kinetic Models predict the reaction between water and cementitious materials under various curing conditions, which is essential for forecasting performance with SCMs 10 .
- Life Cycle Assessment (LCA) evaluates the environmental impact of concrete mixes from raw material extraction to end-of-life, providing the basis for assessing carbon neutrality 11 .
- Durability and Life Models link curing regimes to long-term performance indicators like permeability and shrinkage 12 .
- Carbon Balance Models mathematically combine emissions from material production with savings from carbonation or recycling, forming the core of the carbon-neutral concrete concept 13 .

The development of carbon-neutral concrete began with environmental concerns in the late 20th century. Early work in the 1970s and 1980s involved adding fly ash or slag, marking the birth of "sustainable concrete" 14 . The 1990s and 2000s saw the adoption of LCA and performance-based design codes, further advancing sustainability concepts 15 . Recent decades have witnessed an explosion of innovation, including nanotechnology, geopolymer binders, and CO_2-curing, aligning perfectly with the goal of creating a theoretical model for carbon-neutral mix design under varying curing conditions 16 .

Global Studies and Synthesis

International research converges on three pathways to carbon-neutral concrete: (i) reducing embodied carbon via SCMs like LC^3 (limestone calcined clay cement) and slag; (ii) developing alternative binders like geopolymers; and (iii) implementing curing-centric strategies such as CO_2-curing 17 .

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CO_2 mineralization/carbonation curing is a leading candidate, where fresh concrete mineralizes injected CO_2 into stable carbonates. This process can enhance early strength, enable cement reduction, and sequester CO_2, reducing the net carbon footprint. Technology providers like CarbonCure have demonstrated this at pilot scales 18 .

Low-clinker cements, particularly LC^3, show substantial embodied-carbon reductions and competitive durability. With optimized mix design and curing, LC^3 performs well in aggressive environments, though it may have slightly lower early strength 19 .

Geopolymer concretes often require thermal curing (60–80 °C) to achieve early-age strength. However, recent "ambient-curable" formulations are emerging, which could significantly reduce their energy and water footprint, making them attractive in resource-limited regions 20 .

Internal curing using pre-wetted lightweight aggregates or superabsorbent polymers (SAPs) buffers hydration in low water-to-binder (w/b) systems with high SCM content. This technique reduces shrinkage and improves microstructural density, enhancing durability under non-ideal curing conditions 21 .

Key Findings from the Literature

- CO_2 curing enables "strength-for-cement" swaps, allowing binder reductions for equal performance 29 .
- LC^3 achieves significant embodied-carbon reductions with good durability when curing is properly managed 30 .
- Geopolymer performance is highly dependent on tuned curing scenarios 31 .

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- Internal curing stabilizes low-clinker systems in field conditions 32 .
- Standardized carbon-uptake accounting methods are under development by bodies like RILEM 33 .
- Regional SCM supply constraints are a pragmatic consideration for mix design 34 .

Proposed Conceptual Model

Global evidence confirms that curing is a first-order design variable, not a downstream process. Therefore, the proposed theoretical model must:

- Treat the curing regime as a co-equal design parameter with mix proportions for carbon-performance optimization 35 .
- Incorporate mechanistic links between curing history and long-term performance indicators (e.g., chloride diffusion, shrinkage) for SCM-rich mixes 36 .
- Include carbon accounting modules that credit CO_2 uptake according to standardized methods.
- Represent regional constraints (SCM supply, climate, resource availability) to reflect divergent national pathways.

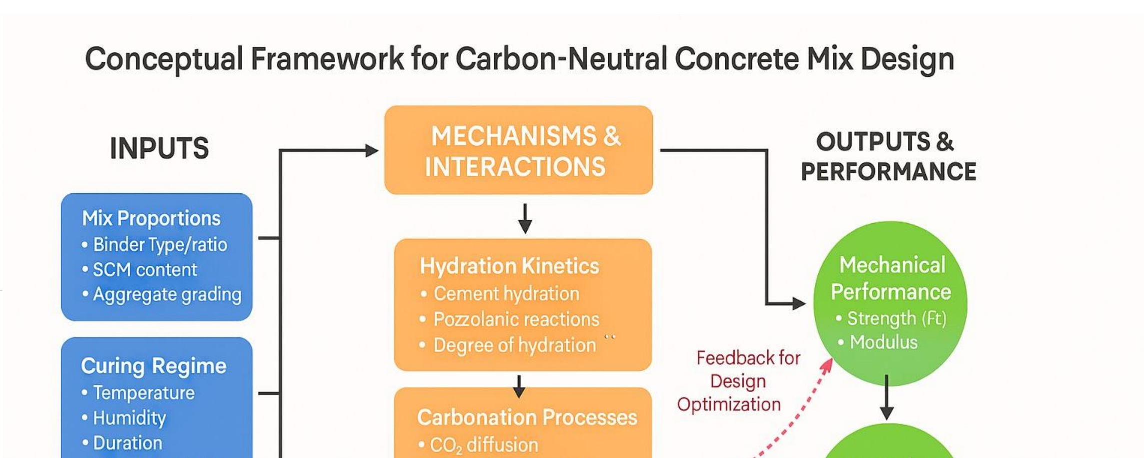

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Figure 1. Conceptual Framework for Carbon-Neutral Concrete Mix Design.

(Description: A flowchart showing "Inputs" (Binder Type & Proportion, Curing Regime) feeding into "Mechanisms" (Hydration Kinetics, Carbonation, Microstructure Development). These mechanisms are influenced by the three intertwined pillars (Environmental, Mechanical, Curing). The mechanisms then lead to "Outcomes" (Compressive Strength, Durability Indicators, Net Carbon Balance), which are evaluated through a feedback loop to optimize the initial inputs.)

Table 1. Integrated Carbon-Neutral Concrete Design Pillars

Pillar	Primary Design Levers	Example Decisions	Core Metrics & Checks

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Environmental	Binder substitution with SCMs; lifecycle boundaries; energy source for curing	Target clinker reduction; select curing route with favorable energy/carbon balance	Embodied CO_2 (cradle-to-gate), credited carbonation uptake, process energy
Mechanical	Proportions of binder/aggregates/admixtures; target strength & durability	Mix optimization to meet strength & transport limits with lower binder	f'c (28d/90d), modulus, transport properties (e.g., D_cl), shrinkage
Curing	Humidity/temperature/time profile; water vs. steam vs. CO_2-curing; internal curing	Select regime that preserves hydration/durability while minimizing energy/carbon	Early-age strength gain, permeability, shrinkage risk, net CO_2 balance
Rationale: Curing must be treated as co-equal with mix design to optimize both performance and carbon outcomes.			

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Regional and Arab Studies

Academic institutions in the Arab world (e.g., Iraq, Egypt, Saudi Arabia) have made significant progress in studying sustainable concrete and partial cement replacement. Universities in Iraq have investigated local pozzolanic materials and supplementary cementitious materials (SCMs), demonstrating benefits for cement reduction and strength under proper curing 37 . Egyptian research has focused on natural pozzolana and agricultural by-products, showing potential for durability in hot, arid climates with appropriate curing. In the Gulf countries, studies on slag-based cements and geopolymers often utilize steam or thermal curing to achieve high early strength for precast applications. These regional studies provide crucial insights for adapting sustainable concrete technologies to local climatic and resource conditions, promoting more durable and environmentally friendly construction in the Middle East 38 . However, they are often limited in scale and lack comprehensive Life Cycle Assessment (LCA) and quantitative carbon accounting compared to international research, highlighting a need for further theoretical development and standardized measurement 39 .

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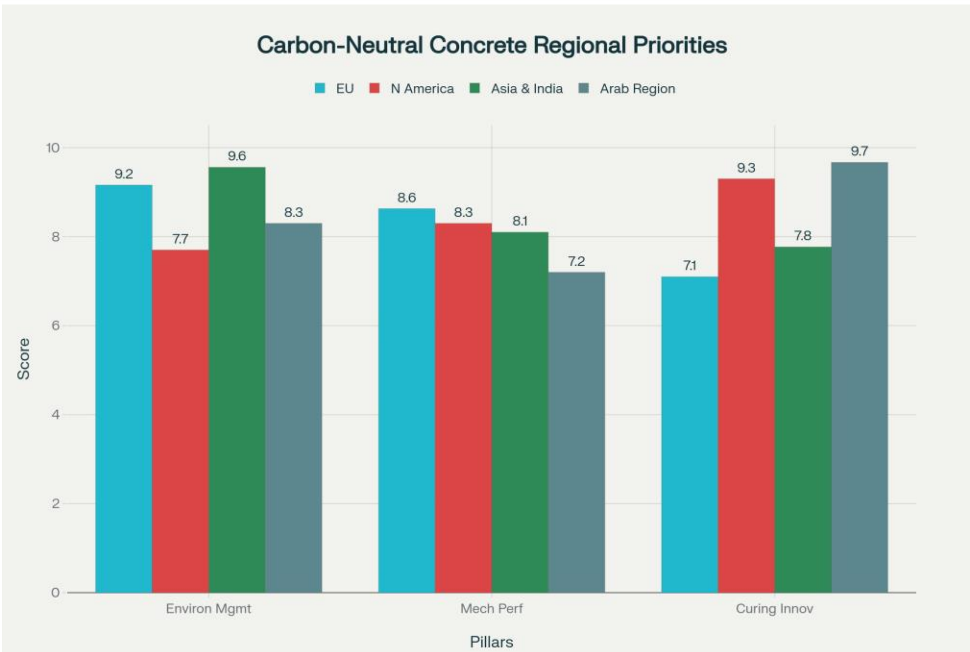

Figure 2. Regional Application of Model Pillars: A Comparison of Focus.

Description: A world map or a multi-panel bar chart comparing different regions (e.g., Europe, North America, Asia/India, Arab Region). For each region, it shows the relative emphasis or research focus on the three pillars: Environmental (e.g., SCM use, LC^3), Mechanical (performance focus), and Curing (method innovation). For example, the Arab Region might show a high focus on Curing and Environmental pillars adapted to hot/dry climates, while North America shows a high focus on Curing (CO_2) and Environmental pillars. Callout boxes can note key regional drivers, e.g., “Water scarcity” for the Arab region, “SCM supply constraints” for North America.

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Practical Applications and Field Experiences

Low-carbon and carbon-neutral concretes are being implemented in real-world projects. In the Middle East, CO_2-curing chambers have been incorporated into precast factories in the U.A.E., reducing curing time and embodied carbon. In Iraq, blended cements with local pozzolans are being used in transport infrastructure, demonstrating improved durability with moist curing. Experimental road sections in Egypt have successfully used concrete containing rice husk ash, valorizing agricultural waste [40].

Challenges to widespread implementation remain [41]:

- Resource constraints: Limited large-scale availability of quality SCMs in some Arab nations.
- Standards gap: A lack of harmonized codes for carbon accounting in concrete complicates project certification.
- Cost trade-offs: Initial investments in advanced curing technology can increase upfront costs, despite cement savings.

These field applications underscore the importance of translating theoretical models into engineering practice. A model that integrates curing conditions can guide engineers in selecting optimal methods (e.g., water, steam, or CO_2 curing) based on local climate and material constraints, making sustainability a pragmatic decision-making factor [42].

Table 2. Comparative Overview of Curing Pathways

Curing Pathway	Process Signal	Effect on Early Strength	Durability Implications	Carbon/Energy Signal	Design Notes

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Water/Moist Curing	Controlled RH, moderate T	Moderate	Favors low permeability; robust for SCM-rich systems	Low process energy; water-intensive	Baseline for durability in warm/dry climates
Steam/Thermal Curing	Elevated T, short duration	High	Risk of coarser porosity if not tuned	High process energy	Useful for precast/geopolymers; check long-term transport
Ambient (Air) Curing	Uncontrolled/limited RH	Low–Moderate	Can harm durability in low RH/hot climates	Low process energy	Requires safeguards (e.g., internal curing) in SCM-rich mixes
CO_2-Mineralization Curing	Early-age CO_2 ingress	Moderate–High	Enables binder reduction at equal performance	Process energy + credited CO_2 uptake (net reduction possible)	Promising for precast; needs standardization

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Conclusion

The development of carbon-neutral concrete presents both a challenge and an opportunity for civil engineering. This review demonstrates that accounting for curing conditions is a critical, yet often secondary, variable influencing both the environmental profile and structural performance of concrete. The proposed theoretical model integrates CO_2 mineralization, moist/steam curing, and internal curing to dynamically link curing processes with hydration kinetics, durability, and lifecycle carbon accounting.

Substantial experimental evidence supports the global potential of CO_2 curing, LC^3 systems, geopolymers, and internal curing. Regional studies from the provide valuable context for implementing these innovations in warm, dry, and resource-constrained settings, though a lack of scaled-up applications and comprehensive LCA remains a limitation. The convergence of global and regional research underscores that sustainability requires adapting general principles to local specifics while adhering to global standards.

Practical barriers, including SCM supply chain limitations and a lack of regional codes for advanced curing methods, highlight the need for a systems-level theoretical framework. Ultimately, achieving carbon neutrality requires more than just reducing cement content; it demands a fundamental rethinking of design paradigms. By integrating curing as a central pillar, this model provides a pathway for engineers to design concretes that are simultaneously structurally sound and environmentally responsible, thereby contributing to the global climate agenda and a more sustainable future for construction.

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