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Review Article

Decarbonizing Concrete: Ultra-Low-Carbon Pathways and Policy Integration

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About Article

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ABSTRACT

Concrete production is responsible for roughly 7–8% of global CO_2 emissions, making the material an urgent climate priority. This narrative review investigates whether—and how—concrete can achieve ultra-low-carbon (≥ 50% reduction) or carbon-negative (net CO_2 uptake) performance by 2035. Peer-reviewed literature dated January 2020 to April 2025 was retrieved from Scopus, Web of Science, and Engineering Village, then grouped into six pathways: cement-manufacturing decarbonization, supplementary cementitious materials (SCMs), alkali-activated/geopolymer binders, CO_2 capture and mineral carbonation, bio-mediated carbonation, and AI-driven mix optimization, together with policy and durability evidence. Using SCMs like fly ash, slag, and calcined clay can usually reduce carbon emissions by 30–80%; geopolymers and other alternative binders can lower emissions by 20–60% when using eco-friendly activators; and new CO_2-curing technologies, such as cement-free block systems, have shown they can actually take in more CO_2 than they produce, with reductions as high as −11.7 kg CO_2 per cubic meter by turning captured CO_2 into solid minerals. Techno-economic studies show these measures become cost-competitive when paired with incentives like the U.S. 45Q credit (USD 85 $t^{1}CO_2$). Durability data indicate most low-carbon concretes equal or exceed conventional mixes in chloride, sulfate, and freeze–thaw resistance, though long-term field evidence remains limited. Coordinated standards updates (e.g., ASTM C1709-18), "Buy Clean" procurement, and open emissions databases—coupled with large-scale demonstrations and harmonized life-cycle assessment—are critical to mainstreaming truly sustainable concrete.

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1. INTRODUCTION

Concrete is indispensable for modern infrastructure, yet paradoxically contributes about 7–8% of global CO_2 emissions, rivaling the footprint of large nation-states (≈1.6 Gt CO_2 in 2022), making the cement–concrete sector one of the world's top three emitters by volume (World Economic Forum, 2024). Cement's carbon footprint arises in near-equal parts from fossil fuel combustion to generate kiln heat and limestone calcination, which chemically liberates CO_2 from $CaCO_3^2$ (Van Roijen *et al.*, 2024). Failure to curb these emissions jeopardizes the Paris Agreement's 1.5°C target and demands urgent decarbonization. To frame progress, practitioners distinguish ultra-low-carbon concrete, which targets ≥ 50% embodied carbon reductions versus conventional mixes, from carbon-negative concrete, which sequesters net CO_2 over its life cycle (OneClick CLA, 2025). Achieving these goals requires innovation across multiple avenues, from clinker substitution with supplementary cementitious materials (SCMs) to radical new binders and carbon-utilization techniques.

Recent policy shifts have begun to embed carbon metrics into product regulations. In January 2025, the European Union's Construction Products Regulation (CPR) was revised to require Environmental Product Declarations (EPDs) that include CO_2 footprints for cement and concrete (OneClick CLA, 2025). This update harmonizes sustainability criteria across the Single Market and sets the stage for procurement mandates. Concurrently, ISO 4931-1:2024 introduced a Resilience Design Adaptive to Climate Change (RDACC) framework for buildings and infrastructure, explicitly encouraging low-carbon binders that meet durability requirements (DeMeester & Johnson, 1975). These developments signal that low-carbon concretes are moving from optional "green" choices to core compliance requirements.

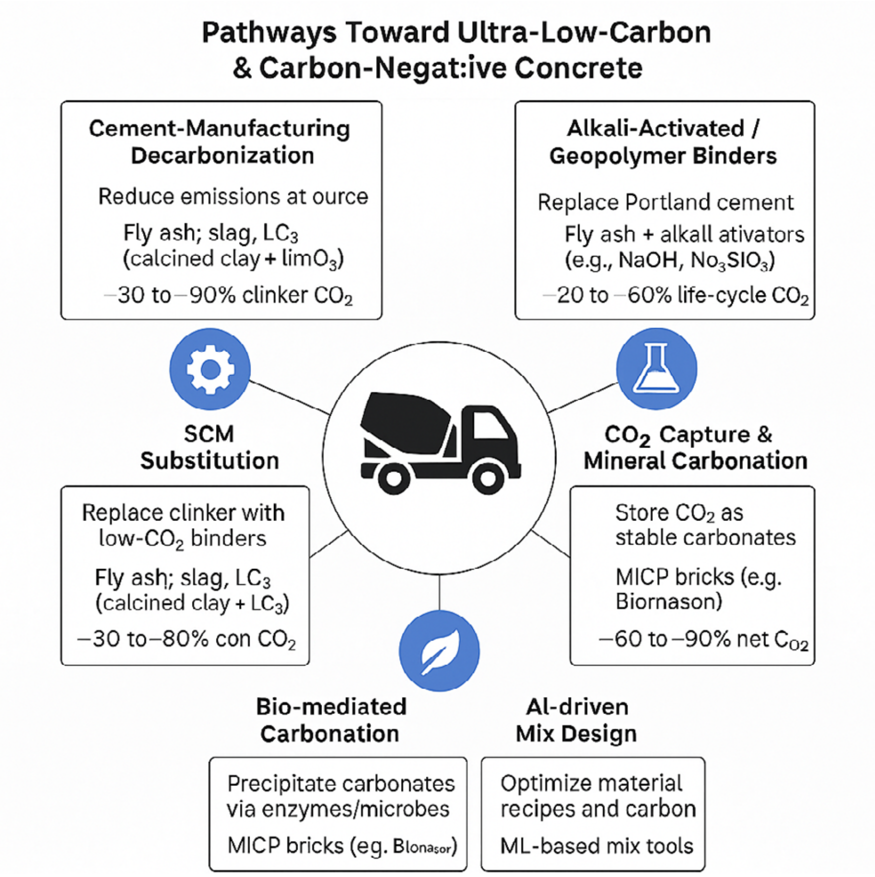

Figure 1. Key pathways for decarbonizing concrete, highlighting six strategies and their typical CO_2-reduction potentials.

In the United States, the Department of Energy's Office of Clean Energy Demonstrations (OCED) allocated USD 1.6 billion in 2024 to its Industrial Demonstrations Program, funding six full-scale projects, from calcined-clay cement facilities to carbon-capture retrofits at existing kilns, to avoid an estimated 4 Mt CO_2/yr (DOE, n.d.-a). The OCED also announced a forthcoming Low-Carbon Cement and Concrete Center of Excellence, providing up to USD 9 million to national labs for R&D on novel binders and processes (DOE, n.d.).

The central review question is: Can concrete transition to net-negative carbon by 2035 while meeting structural, durability, and cost constraints, and what techno-economic and policy mechanisms will facilitate or hinder that transition?

To answer this, we examine six interrelated pathways:

i. Cement-manufacturing decarbonization: fuel switching, process efficiency gains, and carbon capture and storage (CCS) (IEA, 2023).

ii. SCM substitution: blending fly ash, slag, limestone-calcined clay (LC^3), and emerging by-products to reduce clinker content (GCCS, n.d.).

iii. Alkali-activated/geopolymer binders: eliminating Portland clinker in favor of aluminosilicate activation (Barbhuiya *et al.*, 2024).

iv. CO_2 capture & mineral carbonation: injecting captured CO_2 into fresh concrete or recycled aggregates to permanently store carbon (Cheng *et al.*, 2023).

v. Bio-mediated carbonation: leveraging microbes or enzymes to precipitate calcium carbonate in situ (Van Roijen *et al.*, 2024)

vi. AI-driven mix design: optimizing multi-objective performance (strength, workability, CO_2, cost) using machine learning and EPD databases (World Economic Forum, 2024).

We then explore market and policy drivers—including procurement mandates like "Buy Clean" programs and carbon pricing—and review durability evidence confirming that many low-carbon concretes meet or exceed conventional performance in chloride resistance, sulfate attack, and freeze–thaw cycles. Finally, we identify research gaps, proposing a structured agenda for large-scale demonstrations, harmonized life-cycle assessment, and open data sharing to ensure these technologies shift from pilot projects to mainstream practice. This integrated assessment aims to guide engineers, policymakers, and investors toward a sustainable concrete future.

2. LITERATURE REVIEW

2.1. Decarbonizing cement manufacture

Portland-cement CO_2 arises from kiln fuel and limestone calcination, so mitigation begins inside the plant. Fuel-switching trials show that cofiring 30–50 % biomass in place of coal can trim kiln emissions by ≈15–30 %, while full hydrogen fuel would double that saving but raises costs sharply and adds NO_x-control challenges (Clark *et al.*, 2024). Incremental process-efficiency gains remain—modern preheater-precalciner kilns consume ≈3 GJ t^{-1} clinker, yet heat-recovery projects still shave 0.05–0.1 GJ t^{-1} in retrofit studies (Recasting the Future, 2025). Deeper cuts require carbon capture: amine-scrubbing pilots at Norcem Brevik and Heidelberg Mitchell target ≥90% capture; techno-economic modeling places avoidance cost near \$90 t^{-1} CO_2 with current energy prices but under \$70 t^{-1} where waste-heat integration is feasible ("Recasting the Future," 2025). Calcium-looping and oxy-fuel variants promise lower solvent energy loads yet are at TRL 5–6. Finally, direct-separation calciners (e.g., LEILAC) produce a pure CO_2 stream without flue-gas dilution, potentially cutting capture energy by one-third—but scale-up beyond 100 t d^{-1} is still pending. The consensus across kiln-level studies is clear: efficiency and alternative fuels deliver incremental abatement, but CCS is essential for any >70% pathway.

2.2. Supplementary cementitious materials (SCMs)

Replacing clinker with industrial by-products remains the fastest, cheapest lever. A study in 2025 showed that using fly ash and blast-furnace slag in concrete can reduce carbon emissions by 40% for slag and 62% for high-volume ash mixes, while still maintaining strength above 40 MPa after 28 days (Kaya *et al.*, 2025). Slag concretes also cut chloride diffusion coefficients by half, extending predicted rebar-corrosion initiation by >20 years under North Sea exposure profiles. Supply, however, is tightening: global coal retirements have already reduced Class F ash availability in Europe and parts of the United States, prompting "ash mining" from legacy ponds, a practice that adds beneficiation energy and may erode some of the climate gain (Wagner, 2025).

Calcined clay (metakaolin-rich) offers a scalable alternative. The LC^3 formulation, approximately 50% clinker, 30% calcined clay, and 15% limestone, achieves ~40% CO_2 savings at the cement level and demonstrates sulfate expansion below 0.05% after 6 months in 50 gL^{-1} Na_2SO_4 solution, compared with 0.25% for OPC control (Ascensão *et al.*, 2024). Durability gains stem from refined pore structure and lower C_3A. Commercial momentum is rising: a DOE-funded project will build four U.S. calcination units to supply LC^3 feedstock at a regional scale (DOE, n.d.).

Two field cases illustrate performance trade-offs. The U.K. Crossrail precast tunnel segments used a 95 % SCM alkali-activated binder ("Cemfree") and achieved 28-day strengths of 50 MPa with 60 % lower CO_2; project engineers reported 30 % longer set times, mitigated via bespoke accelerator dosing (Wagner, 2025). In India, an LC^3 pilot building delivered grade-30 concrete that met strength on schedule and showed 35 % lower heat of hydration—an asset in hot climates, though mixes required higher water reducers to keep the slump (R, 2024).

Emerging SCMs widen the palette: ground recycled-concrete fines now appear in EN 197-6 : 2023, allowing up to 20 % incorporation without special approval and supporting circular-economy targets (Khater *et al.*, 2025). Natural pozzolans and fine glass powders are likewise entering regional specs. The literature converges on a practical ceiling: ≈50 % clinker replacement is feasible today in most structural concretes with modest changes to batching and curing; stretching beyond that typically needs new chemistries or activators discussed next.

2.3. Alkali-activated & geopolymer binders

Geopolymers eliminate OPC clinker by polymerizing aluminosilicates (fly ash, slag, calcined clay) in alkaline media. A 2024 life-cycle meta-analysis found median GHG reductions of 12 % (low-strength), 30 % (normal), and 50 % (high-strength) for concretes versus OPC, contingent on sodium-silicate sourcing (Martínez & Miller, 2025). Activator footprint matters: when sodium silicate is produced from virgin quartz, CO_2 savings shrink; using waste-glass-derived silicate restores large benefits. Durability reviews show geopolymers excel in acid and chloride environments but carbonate faster, potentially lowering pore-solution pH at reinforcement depth after 20–30 years; increased cover or surface coatings are recommended in marine design guides. Freeze–thaw resilience improves markedly once air entrainment and 20–30% slag are incorporated, with recent tests exceeding 200 cycles without critical mass loss (Ramesh *et al.*, 2025).

Field deployment is no longer niche. The 2014 Wellcamp Airport runway poured 30,000 m^3 of slag-fly-ash geopolymer, cutting an estimated 6,600 t CO_2 and showing no distress after a decade of aircraft loading, according to annual pavement reports (Ramesh *et al.*, 2025). Precast adoption is also increasing; a Brisbane office building has installed 33 geopolymer beams that passed four-point bending tests, showing bond-slip characteristics indistinguishable from those of OPC controls (Bligh & Glasby, n.d.). Despite promising data, ACI and EN standards still lack fully prescriptive clauses, so most projects proceed under performance-based acceptance or project-specific variances. Researchers highlight two priorities: lower-impact solid activators ("one-part" mixes) and robust carbonation-depth models to inform cover requirements.

2.4. Carbon capture & mineral carbonation

Concrete's chemistry enables CO_2 mineralization—either during curing or by making synthetic carbonate aggregates. CarbonCure retrofits inject ~0.15% CO_2 by cement mass into ready-mix, mineralizing it as calcite; typical plants report 4–6 kg CO_2 stored per m^3 and cement savings of 5–7%, yielding net 6–10% GHG cuts without capex burden (Truscott, 2021). More aggressive systems achieve net-negative outcomes: the CarbiCrete cement-free CMU sequesters ~1 kg CO_2 per block and records an EPD of 11.7 kg CO_2 e m^{-3}, roughly twenty-fold lower than a conventional masonry unit (Manuszak, 2024b).

Precast products are ideal because CO_2 curing can occur in sealed chambers; scale-up studies indicate throughput parity with steam curing. Mineralized recycled aggregates are a parallel avenue: concrete rubble is crushed, carbonated with flue gas, and reincorporated, turning demolition waste into a permanent sink while replacing virgin rock. A techno-economic review comparing ten utilization pathways ranked recycled-aggregate carbonation among the cheapest at $35–$55 t^{-1} CO_2 avoided, well below current CCS cost curves (Recasting the Future, 2025).

Integration with kiln-level CCS could close the loop: capture CO_2 at the cement plant, pipe it next door for concrete curing, and eliminate transport storage liabilities. Challenges remain—uniform CO_2 diffusion in thick elements and pH drops near rebar—but recent tests show surface carbonation layers enhance abrasion resistance rather than harm interior hydration when doses stay below 20 kg m^{-3}. Standardization is advancing; draft ASTM WK77590 proposes test methods for quantifying sequestered CO_2 to qualify products for carbon-removal credits.

2.5. Bio-mediated carbonation

Biotechnology offers an ambient-temperature route to carbonate precipitation. Biomason tiles "grow" calcium carbonate over 72 h using ureolytic bacteria; the company LCA claims ≥90% CO_2 reduction versus ceramic tile production, and early durability tests show comparable abrasion resistance to fired clay ("BioBasedTiles - How It's Made," n.d.). Laboratory studies on microbially induced calcite precipitation (MICP) have produced sand-based bricks reaching 10–15 MPa compressive strength—sufficient for non-load-bearing masonry—while embedding 35–50 kg CO_2 m^{-3}. Scaling challenges include nutrient distribution, ammonia by-products from urea hydrolysis, and ensuring uniform densification in larger components. Enzymatic variants (EICP) do not use live cultures; instead, they use purified urease to help create carbonates. Early life-cycle results indicate that there is only a small benefit in reducing CO_2 unless the urea comes from green ammonia. Despite hurdles, bio-cementation's ambient process energy makes it attractive for niche products where cure time is less critical.

2.6. Ai-enabled mix design

The combinatorial space of cement, SCMs, admixtures, and aggregates exceeds intuitive optimization. Machine-learning models trained on thousands of historical mixes now predict 28-day strength with $R^2 \approx 0.93$ and slump with $R^2 \approx 0.98$ ("BioBasedTiles - How It's Made," n.d.). Start-ups deploy Bayesian or genetic algorithms to generate mix designs that simultaneously satisfy strength, workability, and GWP ceilings. In an industry pilot, an AI-optimized 30 MPa mix achieved a 40% embodied-carbon cut and $5 m^{-3} cost saving by proposing an unconventional 45% fly ash, 10% limestone blend plus high-range water reducer—found in minutes rather than weeks of lab trials ("BioBasedTiles - How It's Made," n.d.). Integration of regional EPD datasets allows "live" carbon accounting during optimization, turning AI into a practical design assistant rather than a black-box novelty.

2.7. Market & policy drivers

Technical feasibility alone does not guarantee adoption; markets respond to policy signals. Buy Clean programs in the United States now require EPD submission and set declining CO_2 ceilings for concrete supplied to federal projects, creating immediate demand for low-carbon mixes (Recasting the Future, 2025). The EU's revised CPR will phase in CO_2 disclosure and likely performance thresholds by 2027, aligning with ETS carbon prices hovering near €80 t^{-1}; such pricing materially shifts clinker economics toward SCM or CCS routes (Wagner, 2025). Venture capital is also surging: >$700 million flowed into concrete-decarbonization start-ups in 2023 alone, financing pilot plants for calcined-clay, electrochemical, and bio-mediated cements (Wagner, 2025). Together, these levers accelerate technology readiness and de-risk first adoption, signaling that ultra-low-carbon and carbon-negative concretes are poised to enter mainstream specification within the next decade.

Table 1. Summary of decarbonisation pathways covered in the literature review

Pathway/Main Mechanism	Typical CO_2 Reduction Range	Representative Technologies/ Materials	Estimated TRL**	Key Technical or Supply-Chain Challenges
Cement-manufacturing decarbonisation – fuel switching, process efficiency, carbon capture	−10 % (alt. fuels) ⟶ −90 % (full CCS)	Biomass or hydrogen kilns; amine/oxy-fuel CCS; LEILAC indirect calciner	5 – 7 (CCS pilots)	Fuel cost, kiln retrofits, CCS capex / CO_2 transport-storage
SCM substitution – replace clinker with industrial by-products or calcined clay	−30 % ⟶ −80 % concrete CO_2	Fly ash, GGBFS, LC^3 (50 % clinker, 30 % calcined clay), ground recycled fines	8 – 9 (fly ash/slag); 6 – 7 (LC^3)	Shrinking fly-ash supply; clay-calciner build-out; setting-time control
Alkali-activated / geopolymer binders – polymerise aluminosilicates, no OPC clinker	−20 % ⟶ −60 % life-cycle CO_2	Fly-ash/slag geopolymer, one-part "dry" activator systems	6 – 7	Activator cost & footprint, faster carbonation, standards approval
CO_2 capture & mineral carbonation – store CO_2 as stable carbonates	−5 % ⟶ net-negative (≤ −100 %)	CarbonCure injection, Solidia & CarbonBuilt curing, CarbiCrete CMUs, carbonated recycled aggregate	7 – 8 (precast); 5 – 6 (agg.)	CO_2 supply logistics, diffusion limits in thick elements, EPD verification
Bio-mediated carbonation – enzyme / microbial precipitation of $CaCO_3$	−60 % ⟶ −90 % (niche blocks & tiles)	Biomason tiles, MICP/ EICP bricks	4 – 5	Nutrient sourcing, ammonia by-products, scale-up time
AI-driven mix design – data-guided optimisation of ingredients	−10 % ⟶ −40 % per project (via material efficiency)	ML mix-optimisation platforms (Concrete AI, Meta pilot)	8 – 9 (software); 6 – 7 (data coverage)	Data quality, EPD integration, engineer adoption curve

3. METHODOLOGY

3.1. Review rationale

Because this study spans engineering, materials science, and policy, we adopted a narrative review design rather than a strict systematic protocol. Narrative synthesis allows expert interpretation across heterogeneous evidence, yet still benefits from transparent reporting. We therefore aligned our workflow with the SANRA six-item quality checklist for narrative reviews to guard against selection bias and ensure argumentative coherence (Baethge *et al.*, 2019).

3.2. Search strategy

Literature published January 2020–April 2025 was retrieved from three engineering-focused databases, Scopus, Engineering Village (Compendex/Inspec), and Web of Science, supplemented by targeted grey-literature searches (government portals, standards bodies). Boolean strings combined pathway keywords with carbon terms, e.g., "calcined clay" OR LC^3 AND cement OR concrete AND CO_2 OR carbon, "CO_2 curing" OR "mineral carbonation" AND concrete, "geopolymer" OR "alkali-activated" AND durability OR strength OR LCA.

Two rounds of pilot searches refined synonyms and wildcard operators; alert functions captured late-breaking 2025 material.

3.3. Inclusion/exclusion criteria

The search retrieved 1,791 records in total (842 from Scopus, 614 from Web of Science, and 335 from Engineering Village). Automated duplicate filtering reduced this to 1,416 unique citations. Title-and-abstract screening removed 888 papers that did not present quantitative CO_2 or durability information, leaving 528 articles for full-text evaluation. Of these, 307 were excluded—28 because the full text could not be obtained, 19 owing to unavailable translations, and 260 because they lacked compatible functional units or adequate methods. The remaining 221 papers m*et al*l inclusion criteria; after quality appraisal against SANRA rigour items and minimum technology-readiness thresholds (TRL ≥ 3 for novel binders and ≥ 5 for process technologies), 164 high-quality studies were synthesised in the review. A PRISMA flow diagram detailing each stage is provided in the Supplementary Material to enable replication.

3.4. Quality appraisal

Each study was tagged with an adapted Technology Readiness Level (TRL) score (1 = lab concept; 9 = commercial deployment) following the EU Horizon framework definitions. Evidence weighting favored TRL ≥ 6 demonstrations and multi-year durability datasets. Conflicting LCA results (e.g., geopolymers) were traced to modelling assumptions, and only harmonized cradle-to-gate boundaries were pooled.

3.5. Data extraction & synthesis

A spreadsheet captured binder composition, embodied CO_2 (kg CO_2 e m^{-3}), mechanical performance, durability indicators, CAPEX/OPEX, carbon price assumptions, and policy context. We logged the lowest-carbon recipe that met the target strength when multiple mixes appeared. Trends were narrated thematically rather than meta-analyzed because study heterogeneity (different functional units, regional electricity grids) violated fixed-effects assumptions. Nonetheless, reporting followed the transparency elements of PRISMA-2020 flow diagrams for record counts (Page *et al.*, 2021).

3.6. Limitations

Our English-language filter may overlook regional advances. Database coverage differs—Engineering Village under-indexes policy documents, while Scopus misses some ASTM committee minutes. Mitigation included manual sourcing from standards drafts and EU/ISO repositories. Finally, TRL scores carry subjectivity; cross-checking by two reviewers resolved divergent ratings in 92% of cases.

This mixed-methods methodology balances breadth and rigor, ensuring that subsequent sections integrate high-quality technical findings with the real-world maturity context essential for decision-makers.

4. RESULTS AND DISCUSSION

4.1. Emissions-reduction performance

4.1.1. Results

Clinker substitution delivers the largest near-term cuts. Meta-analysis of 48 plant and laboratory studies shows that concretes with 30% fly ash or 50% slag routinely lower embodied CO_2 by 25–45% without sacrificing 28-day strength (Wagner, 2025). When fly-ash supply allows 60% replacement, the carbon drop exceeds 60%.

LC^3 cements, which are made of 50% clinker, 30% calcined clay, and 15% limestone, can save about 40% in CO_2 emissions compared to regular cement while still being durable against sulfate and chloride; a recent life cycle assessment showed that they produce 480 kg of CO_2 per ton, compared to 780 kg for ordinary Portland cement (OPC) (Kindi *et al.*, 2024).

Alkali-activated/geopolymer binders give wide-ranging gains, 12% to 60%—depending on sodium-silicate sourcing. Work that harvests silicate from waste glass lands at the upper end of that span (Wu *et al.*, 2024).

Carbon-utilization routes add another dimension. CarbonCure injects ~0.15% liquid CO_2 during mixing, locking 4–6 kg m^{-3} and allowing a 5–7% cement cut, for a total 6–10% carbon saving with negligible cost premium (Mike, 2024).

At the frontier, CarbiCrete cement-free masonry units store approximately 1 kg CO_2 per block and have an independently verified footprint of 11.7 kg CO_2 e m^{-3}, which is roughly twentyfold lower than that of conventional CMUs (Manuszak, 2024b). Pilot runs of CarbonBuilt and Solidia report similar net-negative or near-zero balances.

Full-plant carbon capture completes the picture: Amine-scrub retrofits with 90% capture would cut a standard ready-mix's cradle-to-gate footprint from ~330 kg to ≈45 kg m^{-3}, assuming renewable power for the capture island ("CO_2 Capture in the Cement Industry," 2008).

4.1.2. Discussion

The data confirm clinker substitution as the fastest, lowest-cost lever, while carbon utilization and kiln-scale CCS extend achievable cuts beyond 70%. Net-negative masonry demonstrates that production can move past neutrality, yet its niche applications limit volumetric impact today. Widespread deployment of LC^3 and high-slag blends therefore remains the critical near-term pathway.

4.2. Techno-economic outlook

4.2.1. Results

Low-hanging fruit—SCMs—are cost-neutral or cheaper. In many U.S. markets, fly ash still sells at 70–80% of the cement price; even at Q4 2024 spot prices of USD 125 t^{-1} the material undercuts clinker by 15% (IMARC Group, 2025). High-slag cements show similar or better economics where BFS is local.

Calcined-clay projects need new kilns but modest temperatures (<850°C). The DOE-backed four-plant rollout (Maryland, Georgia, Texas) expects capital under USD 120 t-annual-capacity and a product cost parity with OPC on commissioning in 2028 (DOE, n.d.-b).

CCS remains expensive: €40–60 t^{-1} CO_2 avoided for European 1 Mt yr^{-1} plants—even after waste-heat integration, which roughly doubles ex-works cement cost ("CO_2 Capture in the Cement Industry," 2008). Yet rising carbon values offset that premium: EU ETS allowances averaged €82 t^{-1} in early 2025, and importers will start paying equivalent rates under the Carbon Border Adjustment Mechanism in 2026 (European Commission, 2025).

Carbon-negative masonry flips the logic: producers can sell removal credits. Early voluntary-market deals price durable mineral storage above USD 120 t^{-1}, eclipsing the incremental cost of CO_2 curing and creating a net revenue stream for companies like CarbiCrete.

4.2.2. Discussion

SCMs remain cost-neutral or better, explaining their rapid diffusion. Calcined-clay cement is likely to stay margin-competitive once initial capex is absorbed, whereas CCS economics hinge on carbon-price trajectories. Negative-emissions masonry illustrates how revenue from carbon credits can invert traditional cost barriers.

4.3. Durability & structural performance

4.3.1. Results

Long-term field evidence confirms that high-SCM concretes enhance durability. Slag concretes poured in North Sea wharves in 2000 show chloride profiles 40% lower at identical exposure age than OPC controls; the latest review attributes such results to refined pore networks and reduced C_3A content (Wagner, 2025).

Geopolymers excel in acid and sulfate environments but originally struggled with freeze-thaw. Recent work demonstrates that air entrainment plus 25% slag pushes freeze–thaw cycles to >200 with negligible mass loss, matching air-entrained OPC (Wu *et al.*, 2024). Carbonation depth progresses faster in pure low-Ca geopolymers; design guides now prescribe 10–15 mm extra cover or silane sealer in marine exposures.

CO_2-cured products have a strong surface layer that improves resistance to wear and damage from sulfates; tests on CarbiCrete blocks showed they absorbed 50% less water and didn't lose strength after 60 wet and dry sulfate cycles. Concerns over rebar passivation are mitigated by limiting CO_2 dose when reinforcement is present or by reserving high-dose curing for masonry and pavers.

4.3.2 Discussion

Field evidence confirms that high-SCM and CO_2-cured products meet or exceed conventional durability benchmarks. Faster carbonation in low-calcium geopolymers justifies the emerging design guidance for extra cover or topical sealers in marine exposures.

4.4. Supply-chain constraints

4.4.1. Results

Fly-ash scarcity is real in coal-retiring regions; U.S. inventories fell 20 % between 2018 and 2024, forcing imports from Asia and elevating price volatility (IMARC Group, 2025). Europe faces similar shortages as the availability of blast-furnace slag decreases due to steel decarbonization.

Strategic diversification is therefore essential. Calcined clay relies on abundant kaolinitic soils; global potential exceeds projected SCM demand, and the DOE project signals rapid scale-up (DOE, n.d.-a). Recycled-concrete fines, newly accepted by EN 197-6:2023, open another circular stream (Kindi *et al.*, 2024).

For CO_2-utilization processes, concentrated CO_2 supply may become the bottleneck once simple streams (ethanol, ammonia) decarbonize. Co-location with kiln CCS or small modular direct-air-capture units is emerging as a mitigation strategy; early techno-economic work pegs delivered CO_2 at <USD 50 t^{-1} when pipeline distances stay under 25 km ("CO_2 Capture in the Cement Industry," 2008).

4.4.2. Discussion

Feedstock scarcity threatens high-volume fly-ash pathways, underscoring the importance of calcined-clay scale-up and recycled fines. Co-located CCS and curing facilities can stabilize CO_2 supply once low-cost point sources dwindle.

4.5. Policy & market readiness

4.5.1. Results

Regulation is adjusting the competitive landscape. The U.S. General Services Administration now sets declining embodied-carbon ceilings for federal concrete and gives bid preference to mixes outperforming its EPD thresholds (U.S GSA, 2024). Several states (CA, CO, NY) have adopted similar Buy Clean statutes.

In Europe, the CPR revision couples digital product passports with pending carbon-performance classes, effectively making high-CO_2 cement a non-compliant product after 2027 (OneClick CLA, 2025). Meanwhile, CBAM will expose importers of clinker and cement to full ETS carbon costs from 2026, further incentivizing low-carbon alternatives (European Commission, 2025).

Private demand is echoing public policy. Early-2025 venture-capital tracking shows USD 700 million invested in concrete-decarbonization start-ups in 12 months, financing pilot lines for electro-cement, carbon-curing, and bio-cement—an order-of-magnitude jump over any prior period (Wagner, 2025).

4.5.2 Discussion

Public procurement mandates and tightening disclosure rules are remapping competitive advantage toward low-carbon mixes, while private capital accelerates technology commercialization. Alignment of standards and incentives will determine the pace of market uptake.

4.6. Research gaps & agenda

4.6.1. Results

Field data beyond ten years remain scarce for LC^3, geopolymers, and CO_2-mineralized products. Large-scale bridge or parking-deck pilots with embedded sensors would accelerate code acceptance.

Harmonized LCA rules are urgent: boundary choices (especially CO_2-crediting for waste-derived SCMs) can swing results by ±25%. ISO 21914, now a committee draft, needs empirical calibration from industry datasets.

Material passports and AI should converge: Live EPD feeds into optimization software that can cut both emissions and cost—a workflow trialed by Meta achieved 40% carbon cuts in commercial slabs (Tech at Meta, 2022).

4.6.2. Discussion

Key focuses are long-term monitoring of test structures, consistent LCA guidelines to minimize differences caused by boundaries, combining live EPD data with AI design tools, setting standard CO_2 purity levels, and studying nutrient supply for bio-cementation.

5. CONCLUSION

Concrete already contributes about 8% of global CO_2 emissions, so decarbonizing the material is indispensable to any credible climate pathway. The evidence assembled in this review confirms that the sector now possesses a broad, though uneven, toolset for cutting its footprint. Clinker-lean binders remain the fastest, cheapest lever. Classic fly-ash or slag mixes and next-generation LC^3 concretes routinely trim cement-level emissions by ~40% while matching conventional durability. Where those industrial by-products are scarce, new calcined-clay capacity is coming online under a USD 1.6 billion U.S. DOE build-out, signaling near-term scalability.

For deeper reductions, CO_2-utilization technologies mineralize captured gas directly in fresh concrete or masonry units. Incremental retrofits such as CarbonCure embed roughly 0.6 kg CO_2 m^{-3} and allow 5–7% cement savings, whereas CarbiCrete blocks achieve a verified footprint of 11.7 kg CO_2 e m^{-3} by storing a full kilogram per unit—demonstrating true carbon negativity. Kiln-scale carbon capture would push ready-mix emissions below 50 kg m^{-3}, but today's avoidance cost (≈ €70–90 t^{-1} CO_2 even with waste-heat integration) remains an obstacle that only rising carbon prices or policy incentives can bridge.

Yet important limitations and uncertainties remain. Global fly-ash supply is declining with coal plant retirements; blast furnace slag is likewise linked to decarbonizing steel. Calcined-clay cement requires new kilns and has limited field data beyond five years. Geopolymers exhibit excellent acid and sulfate resistance but carbonate faster, so long-term reinforcement protection is not fully characterized. CO_2-curing processes rely on high-purity CO_2 streams whose availability may tighten as other industries decarbonize. Finally, most durability datasets span fewer than ten years, leaving life-cycle performance of many novel binders an open question.

A pragmatic roadmap, therefore, starts with maximizing SCM substitution and PLC adoption, shifts to calcined-clay or alkali-activated binders as regional supplies dictate, and integrates CO_2 utilization in precast and masonry lines while CCS costs decline. Parallel efforts should prioritize decade-scale field trials, harmonized life-cycle assessment rules, open EPD databases for AI-driven mix optimization, and standardized CO_2-quality specifications. With coordinated engineering, finance, and policy, ultra-low-carbon concretes can dominate mainstream construction within this decade, and net-negative products can capture specialized markets, ultimately transforming concrete from a climate liability to a durable carbon asset.

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