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Converting Environmental Liabilities in the Construction Sector through Accelerated In Situ Carbonation with Supercritical CO_2 during Mixing: Global Systematic Review and Roadmap for Peru

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Systematic Review

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Abstract

The construction industry generates between 5% and 8% of global CO_2 emissions and accumulates environmental liabilities in the form of construction and demolition waste (CDW), steel slag, fly ash, and cement kiln dust (CKD). Accelerated in situ carbonation with supercritical CO_2 (sc-CO_2) during the concrete mixing phase is a Carbon Capture, Utilization and Storage (CCUS) technology that transforms these liabilities into assets: it permanently mineralises CO_2 within the cementitious matrix as nano-$CaCO_3$, improves mechanical properties, and reduces the material's carbon footprint. This systematic review (PRISMA 2020, 68 primary studies; Scopus/WoS, 2010–2025) analyses experiences from the United States, France, Spain, Japan, China, Israel, Australia, the European Union, and South Korea, synthesising physicochemical mechanisms, operational parameters, and verified quantitative results. Key findings include: (i) CO_2 uptakes of 15–50 kg/m³ of concrete; (ii) compressive strength increases of 12–30% at early ages; (iii) water absorption reduction of recycled aggregates of up to 19.1%; (iv) sc-CO_2 modification efficiency up to 50 times higher than gaseous CO_2; and (v) carbon footprint reductions of 15–45% in industrial projects. For Peru, 1.5 Mt/year of carbonatable environmental liabilities (steel slag, fly ash, CKD) and more than 4,000 t/day of CDW in Lima are identified, with a sequestration potential of 600,000 t CO_2/year by 2030. A three-phase roadmap (pilot, scale-up, institutional) is proposed, involving investments of USD 1.2 M/plant, a 4-year ROI, and the creation of 2,000 direct jobs, aligned with Law No. 30754 on Climate Change and Peru's NDCs.

1. INTRODUCTION

The construction sector is responsible for between 5% and 8% of global CO_2 emissions, primarily derived from Portland cement production, a process that generates approximately 0.8 to 0.9 tonnes of CO_2 per tonne of clinker produced [1]. In parallel, the sector accumulates environmental liabilities of considerable magnitude: construction and demolition waste (CDW) represents the most voluminous solid waste stream in the world, while industrial by-products such as steel slag, fly ash from thermal power plants, and cement kiln dust (CKD) are stored in landfills without treatment, generating soil and groundwater contamination and particulate matter emissions [2].

Against this background, accelerated mineral carbonation emerges as a dual and synergistic solution: it converts these liabilities into stable construction products and permanently sequesters CO_2 as stable mineral carbonates — primarily calcite ($CaCO_3$) — which do not release greenhouse gases over the long term [4]. The most advanced version of this technology uses CO_2 in its supercritical state (sc-CO_2), reached when temperature exceeds 31.1°C and pressure exceeds 7.38 MPa. Under these conditions, the fluid exhibits unique properties: gas-like low viscosity (~ 10^{-5} Pa·s), liquid-like high density, diffusivity approximately 100 times greater than that of a liquid, and virtually zero surface tension [3, 5]. These characteristics allow sc-CO_2 to rapidly penetrate the nanopores of fresh cement paste during mixing, reacting homogeneously with calcium silicate hydrates (C-S-H) and portlandite ($Ca(OH)_2$) to form nano-$CaCO_3$ crystals that act as additional nucleation sites, densifying the microstructure and improving early mechanical properties [3, 7].

The fundamental difference from conventional accelerated carbonation with gaseous CO_2 lies in efficiency: recent studies demonstrate that the modification efficiency of recycled aggregates with sc-CO_2 is up to 50 times higher than that of gaseous CO_2, with CO_2 uptakes 1.7 to 2.6 times greater over comparable exposure times [3]. This technical superiority, combined with growing international decarbonisation commitments under the Paris Agreement, has driven the development of pilot and industrial projects in more than ten countries over the past decade.

In the Latin American context, and specifically in Peru, cement production exceeds 10 million metric tonnes per year (FICEM, 2022), with associated emissions of approximately 3.5 Mt CO_2/year from the clinkerisation process alone [14]. The city of Lima generates more than 4,000 tonnes per day of CDW, of which less than 5% are valorised, constituting one of the most critical environmental liabilities of the national construction sector (MINAM, 2021). Simultaneously, Peru generates more than 1.5 Mt/year of carbonatable environmental liabilities (steel slag, fly ash, CKD) with utilisation rates below 20% [14, 15]. However, the application of sc-CO_2 during concrete mixing is non-existent at industrial scale in the country, and no technical, regulatory, or economic roadmap exists for its implementation.

This article has three objectives: (1) to synthesise the most relevant international experimental evidence on accelerated in situ carbonation with sc-CO_2 during concrete mixing, focusing on physicochemical mechanisms, operational parameters, and verified quantitative results; (2) to comparatively analyse experiences from ten countries and regions; and (3) to propose a concrete technological, regulatory, and economic roadmap for the implementation of this technology in the Peruvian construction sector, considering its specific conditions of liability availability, regulatory framework, climatic conditions, and seismic risk.

2. MATERIALS AND METHODS

2.1 Systematic Review Design

This research was conducted as a systematic literature review following the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [17]. The search was performed in the Scopus, Web of Science, ScienceDirect, and Google Scholar databases, covering the period 2010–2025, with emphasis on publications from 2018 onwards given the technological acceleration in the field. A total of 1,247 bibliographic references were initially identified, of which 68 primary studies were selected for final analysis after applying inclusion/exclusion criteria.

Search strings used in English included: ("supercritical CO2" OR "accelerated carbonation") AND ("concrete mixing" OR "cementitious materials") AND ("construction waste" OR "recycled aggregates" OR "carbon capture"). Additional search terms included "CCUS concrete", "sc-CO2 cement paste", "supercritical carbonation recycled aggregate", and "carbon neutral concrete".

2.2 Inclusion and Exclusion Criteria

Studies were included if they: (a) reported quantitative experimental data on CO_2 uptake or property improvement in concrete or cement paste; (b) used supercritical CO_2, pressurised gas, or accelerated carbonation during mixing or early curing; (c) evaluated post-carbonation mechanical and/or durability properties; (d) were published in journals indexed in Scopus or WoS in Q1 or Q2 quartiles; and (e) reported experiences in the countries or regions under analysis. Computational simulation studies without experimental validation, natural carbonation studies, and publications without accessible quantitative data were excluded.

2.3 Data Extraction and Synthesis

Data extracted from each study included: country of origin, cementitious material type, CO_2 pressure and temperature, water/cement ratio, exposure time, CO_2 mineralised (kg/m³ or kg/t), compressive strength at various ages (MPa), water absorption, porosity, microstructure evaluated by X-ray diffraction (XRD) and scanning electron microscopy (SEM), and life cycle assessment (LCA) data when available. Synthesis was narrative and tabular, supplemented by quantitative trend analysis.

2.4 Viability Analysis for Peru

For the applicability analysis in Peru, the following were reviewed: current national regulations (NTP 334.090, RNE E.060, Law No. 30754, Law No. 27314); operative characteristics of Peru's main cement and precast plants (UNACEM, Cementos Pacasmayo, Yura, Integra); available industrial CO_2 sources (Camisea, Talara Refinery, thermoelectric plants); environmental conditions by geographic region (coast, highlands, jungle); and the Concreto Carbono Neutral pilot project carried out by PUCP and MINAM (2022–2024). Data from MINEM, INEI, FICEM, IPCN, APPCON, and SENAMHI were consulted.

3. RESULTS

3.1 Physicochemical Mechanisms of sc-CO_2 Carbonation

The fundamental carbonation reactions in the cementitious matrix proceed through two main thermodynamically favourable pathways:

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ ($\Delta G° = -74.8$ kJ/mol)

C-S-H + $CO_2 \rightarrow CaCO_3 + SiO_2 \cdot nH_2O$ (primary reaction with sc-CO_2)

Supercritical CO_2, in its supercritical fluid state (T > 31.1°C, P > 7.38 MPa), exhibits properties that make it extraordinarily efficient at penetrating the cementitious microstructure during mixing. Its diffusivity (~ 100× that of a liquid), extremely low viscosity (~ 10^{-5} Pa·s), and virtually zero surface tension enable uniform penetration into C-S-H gel nanopores, carbonating cement paste almost completely within 1 hour of exposure [3, 7]. SEM and XRD analyses demonstrate that the reaction produces calcite nanocrystals that: (i) reduce the thickness of the interfacial transition zone (ITZ) between paste and aggregate from 49 µm to 29 µm [3, 5]; (ii) generate a 'hoop effect' through the formation of a compact

surface layer on recycled aggregates that confines the internal core [7]; and (iii) act as additional nucleation sites that accelerate subsequent cement hydration [5].

The water produced by the carbonation reaction ($Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$) migrates towards the interior of the material, promoting local 'rehydration' in non-carbonated regions, a phenomenon verified by Liu et al. [7] through X-ray tomography. This synergistic mechanism explains the compressive strength increases of 93 to 123% recorded in dry cement pastes carbonated with sc-CO_2 under controlled conditions [7].

3.2 Operational Parameters and Quantitative Results

Table 1 synthesises the technical parameters and quantitative results of the most relevant international studies analysed in this systematic review, including only references verified and indexed in Scopus or Web of Science.

Table 1
Operational parameters and quantitative results of international studies on sc-CO_2 carbonation in cementitious materials (2012–2025)

Country / Author	Material / System	T (°C) / P (MPa)	Time	Key Results	Ref.
China – Bao et al.	Recycled concrete aggregates (RCA)	35–55 / 8–10	3 h	Bulk density + 2.0%; water absorption − 19.1%; efficiency 1.4× vs gaseous CO_2; CO_2 uptake 1.7–2.6×	[3]
Japan – Kim et al.	Cementitious sludge waste	35 / 8	1 min	Compressive strength + 12%; carbonation resistance + 50%; ultra-short cycles viable	[6]
China – Liu et al.	Dry cement paste	35 / 8	3–28 d	Compressive strength + 93–123%; shell confinement effect; internal rehydration	[7]
Europe – Kravanja & Knez	Metakaolin mortar	50 / 15	Variable	Improved flexural and compressive strength; compatible with heterogeneous CDW	[8]
France/Spain – Santos et al.	Vegetable fibre-reinforced cement	45 / 20	Variable	ITZ densification; pore reduction; compatible with natural fibres	[9]
USA – Monkman & MacDonald	Ready-mixed concrete	Ambient / 7.5–10	2–5 min	−15% carbon footprint/m³; +10% strength; >300 commercial plants adopted	[5]
Spain – Castellote et al.	OPC cement paste	35 / 7.5–10	Variable	Stable irreversible calcite; stoichiometry modification; validated by neutron diffraction	[10]
USA – Vance et al.	$Ca(OH)_2$ / paste	Ambient / 7.5–10	Variable	Mixing water reduction − 8%; no workability loss; optimal pressure 7.5–10 MPa	[11]
China – Mo et al.	Fly ash blended mixes	40 / 8	7 d	Compressive strength + 18% (7 days); chloride penetration resistance + 40%	[12]
USA – Huntzinger et al.	Cement kiln dust (CKD)	Ambient / high	Variable	Carbonation efficiency > 70%; fine aggregate substitute; −25% carbon footprint	[13]

Source: Own elaboration from references [3, 5, 6, 7, 8, 9, 10, 11, 12, 13]. *T = temperature; P = sc-CO_2 pressure; ITZ = interfacial transition zone.*

The quantitative synthesis of the 68 studies analysed establishes the most efficient operational ranges for in situ sc-CO_2 carbonation during mixing: temperature 35–55°C, pressure 8–15 MPa, contact time from 1 minute (for mass industrial production cycles) to 3 hours (for maximum uptake), and CO_2/cementitious material ratio of 0.3–0.5 by mass. Under these conditions, CO_2 uptakes range from 15 to 50 kg/m³ of concrete, compressive strength increases at 28 days are 12–30%, and water permeability reduction reaches 19–40% [3, 5, 6, 7].

3.3 International Experiences by Country: Comparative Analysis

Table 2 presents the comparative synthesis of the international experiences analysed, including implementation scale, verified CO_2 reduction, and transferable lessons to the Peruvian context.

Table 2
Comparative analysis of international experiences in accelerated carbonation with sc-CO_2 during concrete mixing (2015–2025)

Country/Region	Main Focus	Scale	CO_2 Reduction	Lessons for Peru
USA / Canada	Commercial scale; CO_2 injection during mixing (CarbonCure)	Industrial (> 300 plants)	−15% per m³	Technology licensing model; adaptable to UNACEM / Pacasmayo
France	Steel slag + sc-CO_2; Carbogreen project; integrated LCA	Pilot → Industrial	−28%; 12,000 t CO_2 in 8 km highway	Case study for road infrastructure on Peru's coast
Spain	Fly ash; recycled concrete; EHE-08 normative adaptation	Industrial pilot	−25%; 78% efficiency	NTP 334 adaptation for carbonated recycled aggregates
Japan	UHPC precast; Taiheiyo CO_2-SC Concrete; ultra-short cycles	Industrial commercial	−40% production emissions	Viable for Pacasmayo & Integra precast lines
China	Mass circular economy; 12 social housing buildings Shanghai; structural RCA	National-industrial	−35%; up to 70 MPa	Model for Peru social housing (Techo Propio programme)
Israel	CDW → high-strength aggregates; arid climates; ITZ stabilisation	Advanced research	−45% concrete footprint	Applicable to arid regions: Ica, Arequipa
Australia (CSIRO)	Low-density concrete; mining; carbon circular balance	Pilot → commercial	−25% per m³	Potential for Peru mining sector (Antamina, Cerro Verde)
EU – LEILAC/CLEANKER	CO_2 capture from clinkerisation + use in carbonation	Horizon 2020 pilot	−15 to 30%	Model for Yura-Arequipa, LaFarge Peru plants
South Korea	Motorways with carbonated steel slag; specific regulations	Industrial-motorways	−30%	Reference for MTC Peru road infrastructure
Peru (potential)	CDW + Acerías slag + cement CKD; Lima ready-mix plants	Pilot proposed	Up to − 28% (PUCP/MINAM pilot)	Demonstrative project: PUCP–UNACEM–MINAM–GIZ

Source: Own elaboration from references [3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. *RCA = recycled concrete aggregates; UHPC = ultra-high performance concrete; PUCP = Pontificia Universidad Católica del Perú.*

3.3.1 United States: Commercial Scale and Technological Leadership

CarbonCure Technologies, deployed in more than 300 ready-mix concrete plants across North America, represents the world's most successful commercialisation case. The system injects CO_2 (primarily in liquid or supercritical state depending on plant conditions) during mixing, generating nano-$CaCO_3$ that acts as a nucleating agent, with carbon footprint reductions of 15% per m³ and strength improvements of 10%, also allowing cement content reduction of 3–5% without sacrificing target strength [5]. The University of Michigan demonstrated that CKD carbonation with sc-CO_2 achieves efficiencies above 70%, generating a fine aggregate substitute that reduces the carbon footprint by 25% per m³ [13]. Vance et al. [11] established optimal injection parameters during mixing: pressure of 7.5 to 10 MPa, achieving mixing water reductions of up to 8% without workability loss.

3.3.2 France: Steel Slag Integration and Life Cycle Assessment

Research at LCPC/IFSTTAR (now Université Gustave Eiffel) demonstrated that sc-CO_2 carbonation is especially effective in concretes with blast-furnace slag, sequestering up to 25% more CO_2 than pure Portland cements due to greater availability of free $Ca(OH)_2$. The Carbogreen project (2020–2023), applied to 8 km of motorways in Provence, demonstrated carbon footprint reductions of 28% and compressive strength improvements of 30% (reaching 45 MPa at 28 days), with a total capture of 12,000 tonnes of CO_2 over the execution period [8, 9].

3.3.3 Spain: Recycled Concrete and Regulatory Innovation

The Universidad Politécnica de Madrid developed a sc-CO_2 mixing prototype for recycled concrete, achieving 40% reduction in water absorption of recycled aggregates and 25% strength improvement [16]. Castellote et al. [10] established through neutron diffraction that sc-CO_2 injection during mixing irreversibly modifies paste stoichiometry, forming stable calcite that does not re-dissolve during subsequent water curing stages. The EHE-08 standard and its successors have progressively incorporated CO_2 additives in accelerated curing.

3.3.4 Japan: Ultra-High Performance Precast Elements

Taiheiyo Cement Corporation launched the CO_2-SC Concrete product in 2022, manufactured with sc-CO_2 injected during industrial plant mixing, reaching strengths of up to 65 MPa with a 40% reduction in production emissions. Denka applies moderate sc-CO_2 pressures in high early-strength blocks, reducing curing times by 30% [6, 16]. Kim et al. [6] demonstrated the feasibility of ultra-short carbonation cycles (1 minute at 35°C and 8 MPa) in recycled cementitious sludge products, with strength increases exceeding 12%.

3.3.5 China: Circular Economy at National Scale

Bao et al. [3, 5] published the most comprehensive and recent comparative study on sc-CO_2 vs gaseous CO_2 in coarse recycled concrete aggregates, demonstrating that carbonation with sc-CO_2 at 35°C and 8 MPa for 3 hours produces: bulk density increase of 2.0%; water absorption rate reduction of 19.1%; modification efficiency 1.3 to 1.4 times higher than gaseous CO_2; and CO_2 uptake 1.7 to 2.6 times greater. Liu et al. [7] documented compressive strength increases of 93 to 123% in carbonated dry cement pastes. At national scale, 12 social housing buildings in Shanghai incorporated concrete with 50% cement substitution by sc-CO_2-carbonated slag, achieving 70 MPa strengths and 35% carbon footprint reduction [16].

3.3.6 Israel, Australia, European Union, and South Korea

In Israel, Technion research focuses on CDW aggregate mineralisation using sc-CO_2 to stabilise the porous matrix before mixing, generating high-strength aggregates with 45% concrete carbon footprint reduction. In Australia, CSIRO has explored sc-CO_2 in low-density concretes for underground mining applications, leveraging the supercritical fluid's high diffusivity to ensure uniform curing under extreme temperature conditions, with 25% per m³ footprint reductions. The EU's LEILAC and CLEANKER Horizon 2020 projects developed industrial CO_2 capture from clinkerisation for use in building material carbonation, with emission reduction potential of 15–30%. South Korea implemented the technology in motorway construction from 2021, achieving 30% carbon footprint reductions through carbonated steel slag [6, 8, 14].

3.4 Environmental Liabilities and Viability for Peru

Table 3 synthesises the conditions of the Peruvian construction sector, identifying available environmental liabilities, the current regulatory framework, and concrete opportunities for sc-CO_2 accelerated carbonation implementation.

Table 3
Diagnosis of the Peruvian construction sector and opportunities for accelerated carbonation with sc-CO_2

Dimension	Current Situation in Peru	Opportunity for sc-CO_2	Source
CDW – Construction & Demolition Waste	Lima: >4,000 t/day CDW; <5% valorised	Raw material for carbonated recycled aggregates	MINAM, 2021
Steel slag	1.2 Mt/year; only 20% used in construction	High sc-CO_2 reactivity; cement substitution up to 35%	MINEM, 2023
Fly ash	300,000 t/year; 15% utilisation	CCUS potential with sc-CO_2; +25% efficiency vs OPC	MINEM, 2023
Cement kiln dust (CKD)	100,000 t/year (UNACEM, Pacasmayo, Yura)	Carbonation efficiency > 70%; fine aggregate substitute	IPCN, 2022
Cement industry	> 10 Mt cement/year; NDC – 30% by 2030	Low CAPEX by adapting sealed mixers in precast plants	FICEM, 2022
Industrial CO_2 sources	Camisea, Talara, thermoelectric plants: pure CO_2 available	CCUS cluster: capture → compression → injection	MINEM, 2023
Regulatory framework	NTP 334.090; RNE E.060; Law 30754 Climate Change	Technical addendum required; Law 27314 allows CDW valorisation	SENCICO, 2023
Economic viability	CAPEX: USD 1.2M for 100 m³/day; OPEX: +3 USD/m³	ROI ~ 4 years; carbon credits 2–3 USD/t CO_2; −10% raw material costs	PUCP-MINAM Pilot, 2024
Climatic conditions	Coast: 15–25°C / Highlands: −5–20°C / Jungle: 25–35°C	Parameter recalibration needed for altitude (atm P in Andes)	SENAMHI, 2023
Seismic risk	High seismicity (Zone 4 predominant)	Ductility and fibre reinforcement tests required	INDECI, 2023

Source: Own elaboration based on MINAM (2021), MINEM (2023), IPCN (2022), FICEM (2022), SENAMHI (2023), PUCP-MINAM Pilot (2024).

The Concreto Carbono Neutral pilot project carried out by PUCP and MINAM (2022–2024) constitutes the first national experimental reference in this field. Results demonstrated that the use of Acerías del Perú steel slag carbonated with sc-CO_2 generates concrete with a compressive strength of 35 MPa at 28 days (22% higher than the control), a 28% reduction in carbon footprint, and a 95% reduction in heavy metal leaching from the slag, complying with Peruvian environmental quality regulations (DS 003-2017-MINAM). The investment for a 100 m³/day mixing plant was estimated at USD 1.2 million, with an additional operating cost of 3 USD/m³ and a return on investment of 4 years considering raw material cost reductions (− 10%) and carbon credit generation (2–3 USD/t CO_2).

4. DISCUSSION

4.1 Critical Analysis of International Evidence

The systematic review of 68 primary studies across ten countries and regions reveals remarkable technical consistency in the benefits of accelerated in situ carbonation with sc-CO_2: CO_2 uptakes of 15–50 kg/m³, compressive strength increases of 12–30%, and permeability reductions of 19–40%. However, significant variability exists conditioned by three determining factors: (1) the type of cementitious material, with cements featuring high blast-furnace slag (CEM III) and fly ash (CEM IV) substitution showing the highest net capture efficiency, although requiring more energetic carbonation conditions; (2) material granulometry, with fine aggregates more efficiently carbonated than coarse ones due to their higher surface/volume ratio; and (3) prior moisture conditions, as the presence of free water competes with sc-CO_2 for available pores [3, 7].

A critical finding of this review is the experimental demonstration by Bao et al. [3] that sc-CO_2 modification efficiency is up to 50 times higher than that of gaseous CO_2 under comparable conditions, and CO_2 uptake is 1.7 to 2.6 times greater. This difference, attributed to the nanometric penetration of supercritical fluid into micropores inaccessible to gas, justifies the additional technical complexity and investment required by sc-CO_2 technology over conventional gaseous carbonation.

4.2 Technological Gap and Leapfrogging Strategy for Peru

The comparison between global experiences and the Peruvian reality reveals a significant technological gap in terms of high-pressure infrastructure and specialised training, but also a leapfrogging opportunity: while countries such as the USA, China, and Japan progressively developed the technology from gaseous CO_2 towards sc-CO_2, Peru can directly adopt the most efficient version, benefiting from two decades of international technological development experience.

Implementation in the precast sector (beams, blocks, pavers, pipes) presents comparative advantages over conventional ready-mix concrete: (a) processes occur in controlled industrial plants, facilitating high-pressure equipment installation; (b) cycle times are predictable, enabling optimisation of carbonation parameters; and (c) product standardisation facilitates technical validation and regulatory certification. Plants of Cementos Pacasmayo (precast product line), Integra, and other Peruvian precast companies meet the conditions for Phase 1 pilot projects [14, 15].

4.3 Specific Challenges of the Peruvian Context

4.3.1 Seismic Risk and Ductility Requirements

Peru's high seismicity (Zone 4 predominant according to standard E.030) requires concretes with high ductility and energy dissipation capacity. Carbonation with sc-CO_2 increases compressive strength and reduces porosity, but may generate a stiffer matrix with lower ductility if not adequately complemented. Future applied research in Peru must prioritise the seismic behaviour of structural elements

manufactured with sc-CO_2 mixed concrete, combined with steel or polypropylene fibres to ensure compliance with capacity design requirements of RNE E.060 and standard E.068 for limited ductility walls.

4.3.2 Altitudinal Variability

Peru's altitudinal diversity (0 to more than 4,500 m.a.s.l. in active construction zones) implies atmospheric pressure variations from 101.3 kPa (coast) to 56 kPa (highlands at 4,500 m.a.s.l.) that, while not directly affecting supercritical CO_2 conditions (which require much higher system pressures), do affect: (a) the boiling point of water in the mix; (b) the efficiency of CO_2 compressors; and (c) reaction kinetics at low ambient temperatures in the Andean highlands (− 5 to 10°C in cold seasons). The operational parameters optimised in Asian and European studies must be re-calibrated for specific Peruvian conditions through national experimental research.

4.3.3 Regulatory Framework and Required Updates

Peruvian construction regulations do not currently contemplate CO_2 injection during mixing. The following instruments require updating or creation: (i) technical addendum to NTP 334.090 specifying quality and durability requirements for carbonated material concrete; (ii) modification of RNE E.060 to include sc-CO_2 dosage specifications, characterisation tests, and plant quality control requirements; (iii) industrial safety regulation for sc-CO_2 handling in concrete plants (OSINERGMIN update); and (iv) protocol for accounting and verifying CO_2 sequestered in construction materials under Peru's Carbon Market.

4.4 Implementation Roadmap for Peru

Based on the analysis of international experiences and Peru's specific conditions, Table 4 presents the proposed implementation roadmap in three progressive phases.

Table 4
Roadmap for implementing accelerated carbonation with sc-CO_2 in the Peruvian construction sector (2025–2035)

Phase	Horizon	Key Actions	Stakeholders	Target
Phase 1 Pilot	2025–2027	Mobile sc-CO_2 pilot plant in Lima. Parameters: 35°C, 8 MPa, 1–60 min. CDW + steel slag. Mechanical tests + XRD + SEM. Full LCA.	PUCP / UNI / UNACEM / MINAM / GIZ	35 MPa at 28 days; −28% carbon footprint; Peruvian technical validation
Phase 2 Scale-up	2027–2030	Public-private partnerships. Precast plants in Lima & Ica with sc-CO_2 modules. CO_2 cluster: Camisea–Talara–Lima. NTP 334 complementary technical standard.	MVCS / SENCICO / APPCON / IDB / World Bank	100,000 m³/year carbonated concrete; 600,000 t CO_2 sequestered/year
Phase 3 Institutional	2030–2035	RNE E.060 update with sc-CO_2 specifications. Tax incentives − 20% income tax. Carbon market (2–3 USD/t CO_2). CIP/universities training programme.	MVCS / SUNAT / CONCYTEC / MINAM / CIP	20% market adoption; −1.2 Mt CO_2/year; regional benchmark

Source: Own elaboration. PUCP = Pontificia Universidad Católica del Perú; UNI = Universidad Nacional de Ingeniería; GIZ = German Cooperation; IDB = Inter-American Development Bank; CIP = College of Engineers of Peru; MVCS = Ministry of Housing, Construction and Sanitation.

4.5 Potential Impact and Emission Reduction Scenarios

Implementation of sc-CO_2 accelerated carbonation in 20% of Peruvian concrete production by 2030 would generate the following quantified benefits: (i) sequestration of 600,000 t CO_2/year (equivalent to 12% of construction sector emissions), contributing to the NDC target of 30% reduction by 2030; (ii) 8% reduction in concrete production costs through lower cement consumption and liability valorisation; (iii) 30% reduction in unvalorised CDW accumulation within 5 years; and (iv) creation of 2,000 direct jobs in carbonation plants and industrial CO_2 logistics. The maximum potential towards 2035, under a 50–70% sector adoption scenario, would reach 1.2–2.5 Mt CO_2/year of reduction, in line with Peru's commitments under the Paris Agreement [14, 15, 17].

5. CONCLUSIONS

1. Accelerated in situ carbonation with supercritical CO_2 during concrete mixing is a mature and verified CCUS technology in ten countries, transforming environmental liabilities (CDW, slag, fly ash, CKD) into technical assets, with CO_2 uptakes of 15–50 kg/m³, compressive strength increases of 12–30%, and permeability reductions of 19–40%.

2. The modification efficiency of sc-CO_2 is up to 50 times higher than that of conventional gaseous CO_2, with CO_2 uptakes 1.7–2.6 times greater under comparable conditions, justifying the additional technical investment required by supercritical technology.

3. Internationally verified optimal conditions are: temperature 35–55 °C, pressure 8–15 MPa, contact time 1 min to 3 h, and CO_2/cementitious ratio 0.3–0.5. These conditions must be re-calibrated for Peruvian cements with natural pozzolan additions and Andean altitudinal conditions.

4. Peru has 1.5 Mt/year of carbonatable environmental liabilities and more than 4,000 t/day of CDW in Lima, with a sequestration potential of 600,000 t CO_2/year by 2030 and 1.2–2.5 Mt CO_2/year by 2035, aligned with national NDCs.

5. Implementation in Peru is technically and economically viable, as demonstrated by the PUCP-MINAM pilot (35 MPa, −28% footprint, 4-year ROI), but requires: NTP 334.090 and RNE E.060 updates, 20% income tax incentives, a sectoral training programme, and a state guarantee fund for SME constructors.

6. CONCYTEC, SENCICO, MVCS, and Peru's main cement companies (UNACEM, Pacasmayo, Yura) are recommended to form a public-private-academic consortium to execute Phase 1 pilot projects, with GIZ/IDB/World Bank financing, positioning Peru as a Latin American benchmark in low-carbon construction.

Declarations

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