Brief Report

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Carbon Dioxide Sequestration Through Innovative Cementitious Construction Materials: Strategic Relevance in the Context of the 2026 Global Energy Crisis

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Abstract

The ongoing energy crisis triggered by disruptions around the Strait of Hormuz is reshaping the economics of the global construction sector. Rising energy costs and supply chain disruptions are increasing production costs for conventional building materials such as cement, steel, and plastics, all of which are highly energy-intensive. This context intensifies the strategic relevance of materials capable of sequestering carbon over their life cycle, which offer the dual benefit of reduced energy consumption in manufacture and long-term climate benefit. Against this backdrop, this paper provides an updated overview of the accelerating global warming crisis, incorporating the most recent scientific evidence, and presents a comprehensive account of distinct classes of cementitious construction materials with CO_2 sequestration capacity. This paper also addresses the principal barriers to large-scale deployment and explores the landmark EU Energy Performance of Buildings Directive underscores the persistent lack of robust global regulations requiring real estate investors to disclose embodied carbon emissions.

Keywords: energy crisis; CO_2 emissions; embodied carbon; EPBD

1.1. The 2026 Energy Crisis and the Case for Carbon-Sequestering Construction Materials

The ongoing energy crisis triggered by disruptions around the Strait of Hormuz has already driven global energy prices sharply higher and affected the cost and availability of key construction inputs such as oil-derived products, aluminium, and petrochemicals. Following the effective closure of the strait to commercial shipping from early March 2026 — the result of military conflict in the region — Brent crude oil prices surpassed $100 per barrel for the first time in four years, rising to a peak of $126 per barrel. The International Energy Agency (IEA) described the closure as the "greatest global energy security challenge in history," characterising it as the largest supply disruption to the global oil market ever recorded (WEF, 2026). Some 20 million barrels of oil per day — approximately 20% of global seaborne oil trade — normally transit the strait, along with around 20% of global liquefied natural gas (LNG) trade, primarily from Qatar. With supply chains and freight routes disrupted, energy costs have surged across industries including building materials production. Reported price increases in aluminium, plastics, methanol, and petrochemicals — all significant construction inputs — are raising production costs for conventional materials like cement, steel, and synthetic products, which are highly energy-intensive and sensitive to fuel prices (WEF, 2026). The European construction and chemical sectors have already reported cost surcharges of up to 30% to offset surging electricity and feedstock costs.

At the same time, there is increasing awareness in engineering and sustainability research of the environmental impact of traditional construction materials, which account for a significant share of embodied energy and carbon emissions, and of the potential for alternative materials to reduce both energy use and carbon footprints in buildings. In this combined context of elevated energy costs and

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intensified focus on decarbonisation, the construction sector is gradually shifting toward solutions that are not only competitive in a high-energy-price environment but also aligned with broader sustainability goals. Materials capable of sequestering carbon over their service life — including bio-based products such as sustainably sourced timber and hemp composites, as well as the cementitious materials that are the focus of this book — are gaining strategic relevance because they offer both reduced energy consumption in manufacture and long-term climate benefits. The present paper focuses specifically on cementitious materials with CO_2 sequestration capacity, a class of solutions that combines the ubiquity and structural performance of concrete with the potential to act as a durable carbon sink at global scale.

This economic imperative reinforces a scientific urgency that is itself increasingly acute. During the early 18th century, coinciding with the onset of the Industrial Revolution, the atmospheric CO_2 level stood at 280 ppm. The year 2016 marked a symbolic milestone as the first in which atmospheric CO_2 levels remained consistently above 400 ppm throughout the entire year (Betts et al., 2016). By 2024, the situation had become dramatically more acute. The World Meteorological Organization (WMO) reported that the globally averaged CO_2 concentration reached 423.9 ppm in 2024 — an increase of 3.5 ppm over 2023, the largest single-year rise since modern measurements began in 1957 (WMO, 2025).

The planetary boundary of 350 ppm identified by Rockström et al. (2009) was breached long ago. Even if all greenhouse gas emissions ceased immediately, the thermal inertia of climate systems means rising seas, ocean acidification and extreme weather would continue for at least a century (Clayton, 2001). This makes negative emissions — the extraction of CO_2 from the atmosphere — an engineering imperative rather than an option (Hansen et al., 2017), and constitutes one of the Grand Challenges of Engineering (Mote et al., 2016).

There are currently two principal market-based instruments for reducing CO_2 emissions: emissions trading systems (ETSs) and carbon taxes. Academic analysis has generally favoured carbon taxes as more economically efficient (Wesseh et al., 2017; Zhang et al., 2017), yet real-world implementation has remained politically contested. Paradoxically, the ongoing energy crisis may create a new opening for carbon pricing instruments: when the full economic costs of fossil fuel dependence become visible through price shocks, the relative competitiveness of low-carbon alternatives improves without any policy intervention.

Nevertheless, global progress on carbon pricing has been substantial. Revenues exceeded $100 billion for the first time in 2024. Some 80 carbon pricing instruments — 43 carbon taxes and 37 ETSs — now cover approximately 28% of global greenhouse gas emissions (World Bank, 2025). China expanded its national ETS to the cement, steel, and aluminium sectors in March 2025 (OECD, 2025). The EU’s Carbon Border Adjustment Mechanism (CBAM) will impose fees on the CO_2 content of imported cement and steel, creating new incentives for low-carbon construction materials at precisely the moment when energy costs make them economically competitive.

Direct air capture (DAC) has attracted enormous interest, but the scale gap remains staggering. In May 2024, Climeworks inaugurated “Mammoth” in Iceland, designed to capture up to 36,000 tonnes of CO_2 per year — nine times the capacity of its predecessor, Orca (Climeworks, 2024). Yet actual capture in 2024 totalled only approximately 105 tonnes, exposing the vast chasm between design ambitions and operational reality (Barnard, 2025). Geological CO_2 storage in saline aquifers carries large risks and very high costs (Zhang and Huisingh, 2017), while carbon capture and storage from industrial point sources remains technologically immature at global scale (Langie et al., 2022). Annual removal of between 3,500 and 9,800 million tonnes of carbon will nonetheless be required over the next 30 years (TE, 2023a). This imperative, combined with the economic disruptions of the current energy crisis, elevates cementitious construction materials with inherent or engineered CO_2 sequestration capacity to the status of a globally strategic priority. Pacheco-Torgal et al. (2024) have provided a comprehensive overview of carbon dioxide storage-based cementitious construction materials, presenting a promising avenue for substantial eco-efficiency and economic advantages within the construction sector. The first part of that volume examines different methods and mechanisms for carbon dioxide sequestration in cementitious materials, including in steel slag, in magnesium-based binders, and in autoclaved cement mixtures. Part two explores carbon capture in industrial waste and recycled materials, considering cost, energy, and aqueous carbonation kinetics. The final part is entirely new and investigates biological approaches to carbon dioxide sequestration in construction materials, involving bacteria, bamboo biochar, wood bio-concretes, and bio-inspired materials. This paper reviews recent literature on five classes of cementitious construction materials with carbon sequestration capacity.

1.2. CO_2 Sequestration Through Cementitious Construction Materials

Concrete and cement-based materials constitute a globally significant and largely underappreciated CO_2 sink. Xi et al. (2016) demonstrated that a cumulative 4.5 GtC was sequestered in carbonating cement materials between 1930 and 2013, offsetting 43% of cement production CO_2 emissions over the same period. A subsequent update by Huang et al. (2023) estimated accumulated global CO_2 uptake from 1930 to 2021 at 22.9 Gt CO_2. Most recently, Niu et al. (2025) — in the most comprehensive national-level analysis ever conducted, covering 163 countries and regions with 58,517 activity data points and 6,186 carbonation parameters — extended this accounting to 2024, projecting global CO_2 uptake by cement carbonation at approximately 0.86 Gt CO_2/year: concrete absorbs 0.40 Gt/year, mortar 0.38 Gt/year, cement kiln dust 0.06 Gt/year, and construction losses 0.027 Gt/year. This represents more than half of cement production process emissions of approximately 1.6 Gt CO_2/year in 2023. This body of evidence confirms that the carbonation of cement-based materials is a substantial and growing carbon sink whose significance is systematically underestimated in national greenhouse gas inventories.

Luo et al. (2024) modelled a concrete cycle centred on construction and demolition (C&D) waste recycling with integrated CO_2 sequestration. Their analysis shows that per tonne of recycled cement produced, CO_2 emissions are reduced by 47–94% relative to ordinary Portland cement. If recycled cement were to replace OPC at the global scale, the potential annual CO_2 sink could reach 1.4–3.08 Gt. In the current energy crisis context, recycled cement also offers the additional advantage of significantly lower energy consumption in production, making it doubly attractive.

The carbonation process is, however, double-edged: late-stage natural carbonation reduces the pH of concrete, promoting reinforcement corrosion. The pre-curing approach using sodium bicarbonate disclosed by Stefaniuk et al. (2023) offers a promising pathway to overcome this limitation, enabling CO_2 to be permanently mineralised into calcium-silicate-hydrate (CSH) without compromising reinforcement protection.

Accelerated carbonation curing (ACC) — in which cement products are exposed to elevated CO_2 concentrations before or during curing — has become one of the most active frontiers in sustainable construction research. Wang and Fan (2025) map the full landscape of ACC strategies. Xie et al. (2025) provide a complementary mechanistic review demonstrating that ACC simultaneously sequesters CO_2 and improves mechanical properties and durability. Liu et al. (2025) further systematise the mechanisms, techniques, and precursor materials in enforced carbonation for low-carbon concrete.

A particularly innovative contribution comes from Fu et al. (2024), who developed a novel approach in which CO_2 is injected into a cement suspension subsequently used to manufacture concrete. By converting the carbonation reaction from a diffusion-controlled process into an aqueous ionic reaction, this method achieves a CO_2 sequestration efficiency of up to 45% while maintaining uncompromised concrete strength. The approach is technologically simple and thus amenable to rapid industrial adoption. In the context of the current energy crisis — which is raising the cost of energy-intensive conventional concrete production — the potential to sequester CO_2 during an otherwise standard manufacturing step, without additional structural penalty, constitutes a compelling economic argument as well as an environmental one.

Machine learning is now being applied to optimise ACC systematically. Sun et al. (2025) demonstrate that data-driven models can accurately predict CO_2 sequestration in cementitious materials as a function of mix composition and curing conditions, enabling the computational design of mixtures that maximise carbon uptake. A comprehensive bibliometric analysis by Liang et al. (2025) confirms that mineral carbonation of civil engineering materials is one of the most rapidly growing research topics in sustainable construction.

Geopolymers and alkali-activated materials (AAMs) represent an entirely distinct class of construction binder with significant CO_2 sequestration potential and substantially lower embodied energy than Portland cement. Kriven et al. (2024) make the case that geopolymers and AAMs are "key components of a sustainable world," proposing a comprehensive strategy for regulatory integration and market scale-up. The lower energy intensity of geopolymer production — which does not require the high-temperature calcination of limestone — is particularly relevant in a high-energy-cost environment: LCA studies consistently report CO_2 emission reductions of 40–80% relative to OPC, primarily by eliminating the calcination step and leveraging industrial by-product precursors such as fly ash and ground granulated blast furnace slag. Tushar et al. (2025), in the first fully probabilistic LCA of geopolymer concrete production using Monte Carlo simulation across 580 mix designs, quantified a mean reduction of 43% in carbon emissions relative to conventional concrete, while critically revealing that even modest increases in chemical admixture content can significantly offset these environmental gains — a finding with direct implications for mix design optimisation.

The deliberate integration of CO_2 into geopolymer systems is now recognised as a distinct sequestration pathway. Sahoo et al. (2024) demonstrated that accelerated carbon curing (ACC) in alkali-activated mortars incorporating lateritic clay increases 1-day compressive strength by 13% and reduces total shrinkage by 25%, though long-term natural carbonation over 365 days caused decalcification in low Ca/Si ratio materials — an important durability caveat that constrains precursor selection. Ghazouani et al. (2025) introduced the conceptually innovative approach of aerating CO_2 directly into the NaOH activator solution before geopolymer synthesis, achieving 47.86 MPa at 28 days alongside improved pore structure. At the system level, Sun et al. (2025a) identified a critical structural threshold — 55% of pores below 10 nm — that governs the transition between complete and incomplete carbonation in ternary solid waste geopolymers, achieving a maximum CO_2 uptake of 12.7% and establishing a mechanistic framework for optimising carbonation initiation timing within standard 28-day construction schedules.

A further step change is represented by the application of supercritical CO_2 curing to lignite-based fly ash geopolymer mortars, which achieved a carbonation rate of 67% — far exceeding those attained under conventional atmospheric or pressurised gas conditions — alongside simultaneous improvements in compressive and flexural strength (Podnat et al., 2025).

Biochar — a carbon-rich material produced from biomass in an oxygen-limited environment — has emerged as a promising additive for construction materials owing to its intrinsic carbon sequestration capacity and its ability to promote CO_2 uptake via accelerated carbonation. Zhou et al. (2025) identify conditions under which biochar-modified materials achieve net-negative carbon footprints: specifically, approximately 30 wt% aggregate substitution under CO_2 curing, delivering a net-negative footprint at an economic value of approximately $41 per cubic metre. At 5% biochar blending, a carbon-negative effect of 541–980 kg CO_2eq/tonne is achievable. The use of agricultural and forestry residues as biochar feedstocks is also relevant to the energy crisis context, as biomass-derived materials are insulated from fossil fuel price shocks.

Reactive magnesia (MgO) cements undergo carbonation curing to form hydrated magnesium carbonates as their primary binding phases, with each kilogram of carbonated reactive MgO cement capable of sequestering up to 0.78 kg of CO_2. Tan et al. (2024), through a comprehensive life cycle assessment, demonstrate that using MgO derived from salt lake magnesium residues reduces CO_2 emissions by over 60% relative to conventional MgO, and that CRMC achieves compressive strengths up to three times higher than OPC. The calcination temperature for reactive MgO production (700–1000 °C) is substantially lower than for Portland cement clinker (up to 1450 °C), offering significant energy savings that are especially valuable in the current high-energy-cost environment.

Table 1. Comparative overview of five cementitious material classes with CO_2 sequestration capacity: indicative uptake values, CO_2 reduction relative to OPC, energy intensity, and technology readiness level.

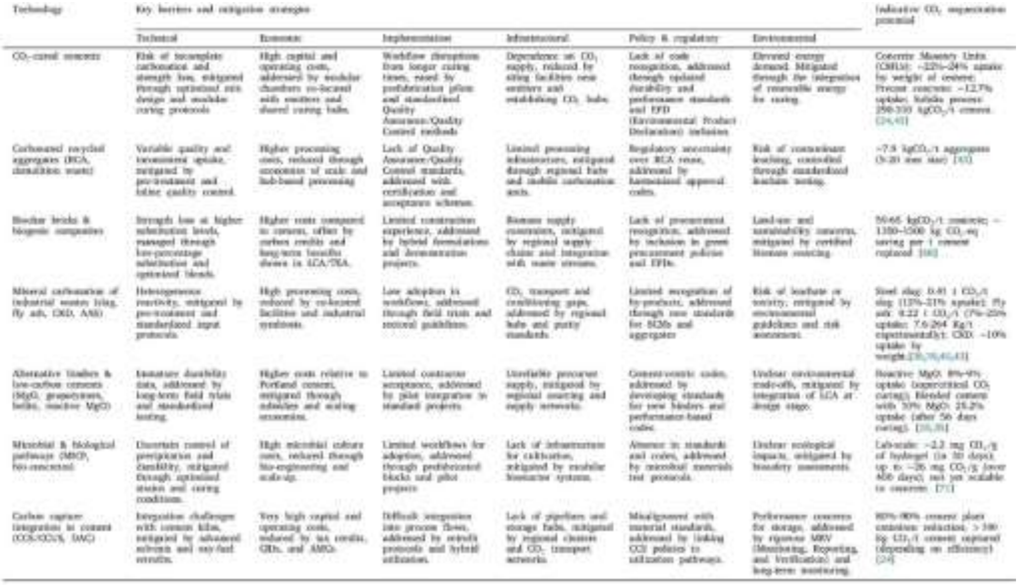
Material Class	CO_2 Uptake (indicative)	CO_2 Reduction vs OPC (%)	Energy Intensity vs OPC	Technology Readiness Level	Key Reference
Accelerated Carbonation Curing (ACC)	Up to 45% sequestration efficiency (Fu et al., 2024)	20–40%	Similar to OPC; no additional calcination	TRL 6–8 (pilot/pre-commercial)	Wang & Fan (2025); Fu et al. (2024)
Geopolymers / Alkali-Activated Materials (AAMs)	Up to 12.7% CO_2 uptake by mass (Sun et al., 2025a)	40–80%	Significantly lower (no limestone calcination)	TRL 5–7 (varies by precursor)	Kriven et al. (2024); Tushar et al. (2025)
Recycled Cement (C&D Waste)	Potential sink of 1.4–3.08 Gt CO_2/year at global scale (Luo et al., 2024)	47–94%	Substantially lower (avoids virgin clinker production)	TRL 4–6 (lab/demonstration)	Luo et al. (2024)
Biochar-Modified Cementitious Materials	541–980 kg CO_2eq/t at 5% blending (Zhou et al., 2025)	Net-negative at ~30 wt% under CO_2 curing	Lower (biomass-derived; fossil-fuel insulated)	TRL 4–6 (emerging; lab-scale)	Zhou et al. (2025)
Reactive MgO Cement (CRMC)	Up to 0.78 kg CO_2/kg MgO (Tan et al., 2024)	>60% (salt lake MgO source)	Lower calcination temp (700–1000 °C vs 1450 °C for OPC)	TRL 5–7 (pilot scale)	Tan et al. (2024)

1.3. Barriers to Large-Scale Deployment, Embodied Carbon Regulation and the EPBD 2024

1.3.1. Barriers to Large-Scale Deployment

Despite the compelling scientific evidence reviewed in section 1.2, the penetration of these materials into the construction market remains limited. Jouamai et al. (2025) conducted a systematic scoping review identifying seven barrier domains that obstruct large-scale deployment: technical, economic, implementation, policy and regulatory, environmental, infrastructural, and cross-cutting social factors. Table 2 makes this connection by comparing leading sequestration pathways across six domains: technical, economic, implementation, infrastructure, policy and regulation, and environment. while also adding indicative CO uptake values. In this way, the table highlights not only the types of barriers that recur across technologies, such as high capital costs or limited CO transport, but also the very different scales of sequestration they can achieve. Technical barriers are the most varied across the five material classes. For ACC, the principal constraints are the limited industrial availability of concentrated CO_2 streams, the sensitivity of carbonation kinetics to moisture content and mix design, and the durability concerns associated with late-stage natural carbonation reducing concrete pH and promoting reinforcement corrosion. For geopolymers and AAMs, the main technical obstacles are the variability in precursor composition (fly ash and GGBS quality fluctuates significantly by source and geography), the lack of standardised mix design protocols, and the limited long-term durability data under field conditions. For biochar-modified materials, the heterogeneity of biochar feedstocks and the absence of harmonised characterisation methods limit reproducibility across studies. For reactive MgO cements, the sensitivity of carbonation efficiency to curing humidity and CO_2 concentration, combined with limited preclinical performance data at structural scale, remains a constraint. Recycled cement faces technical barriers around quality control of demolition waste streams and the mechanical performance penalty associated with residual paste porosity.

Table 2. - Comparative matrix of leading carbon-sequestration technologies in construction, their key barriers, mitigation strategies, and indicative CO sequestration potential (Jouamai et al., 2025).



Technology	Key barriers and mitigation strategies						Indicative CO_2 sequestration potential
	Technical	Economic	Implementation	Infrastructural	Policy & regulatory	Environmental	
CO_2-cured concrete	Risk of incomplete carbonation and strength loss, mitigated through optimised mix design and modular curing protocols	High capital and operating costs, addressed by modular chambers co-located with emitters and shared curing hubs.	Workflow disruptions from longer curing times, eased by prefabrication pilots and standardised Quality Assurance/Quality Control methods	Dependence on CO_2 supply, reduced by siting facilities near emitters and establishing CO_2 hubs.	Lack of code recognition, addressed through updated durability and performance standards and EPD (Environmental Product Declaration) inclusion	Elevated energy demand. Mitigated through the integration of renewable energy for curing	Concrete Masonry Units (CMUs): ~22%–24% uptake by weight of cement; Precast concrete: ~12.7% uptake; Solidia process: 250–330 kgCO_2/t cement [24,41]
Carbonated recycled aggregates (RCA, demolition waste)	Variable quality and inconsistent uptake, mitigated by pre-treatment and inline quality control.	Higher processing costs, reduced through economies of scale and hub-based processing	Lack of Quality Assurance/Quality Control standards, addressed with certification and acceptance schemes.	Limited processing infrastructure, mitigated through regional hubs and mobile carbonation units.	Regulatory uncertainty over RCA reuse, addressed by harmonised approval codes.	Risk of contaminant leaching, controlled through standardised leachate testing.	~7.5 kgCO_2/t aggregate (5-20 mm size) [43]
Biochar bricks & biogenic composites	Strength loss at higher substitution levels, managed through low-percentage substitution and optimised blends.	Higher costs compared to cement, offset by carbon credits and long-term benefits shown in LCA/TEA.	Limited construction experience, addressed by hybrid formulations and demonstration projects.	Biomass supply constraints, mitigated by regional supply chains and integration with waste streams.	Lack of procurement recognition, addressed by inclusion in green procurement policies and EPDs.	Land-use and sustainability concerns, mitigated by certified biomass sourcing	50-65 kgCO_2/t concrete; ~1350–1500 kg CO_2-eq saving per t cement replaced [16]
Mineral carbonation of industrial wastes (slag, fly ash, CKD, ASH)	Heterogeneous reactivity, mitigated by pre-treatment and standardised input protocols.	High processing costs, reduced by co-located facilities and industrial symbiosis.	Low adoption in workflows, addressed through field trials and sectoral guidelines.	CO_2 transport and conditioning gaps, addressed by regional hubs and purity standards.	Limited recognition of by-products, addressed through new standards for SCMs and aggregates	Risk of leachate or toxicity, mitigated by environmental guidelines and risk assessment.	Steel slag: 0.41 t CO_2/t slag (12%–21% uptake); Fly ash: 0.22 t CO_2/t (7%–25% uptake; 7.6-264 Kg/t experimentally); CKD: ~10% uptake by weight [26,70,40,41]
Alternative binders & low-carbon cements (MgO, geopolymers, belite, reactive MgO)	Immature durability data, addressed by long-term field trials and standardised testing.	Higher costs relative to Portland cement, mitigated through subsidies and scaling economies.	Limited contractor acceptance, addressed by pilot integration in standard projects.	Unreliable precursor supply, mitigated by regional sourcing and supply networks.	Cement-centric codes, addressed by developing standards for new binders and performance-based codes.	Unclear environmental trade-offs, mitigated by integration of LCA at design stage.	Reactive MgO: 8%–9% uptake (supercritical CO_2 curing); Blended cement with 30% MgO: 25.2% uptake (after 56 days curing). [35,39]
Microbial & biological pathways (MICP, bio-concrete)	Uncertain control of precipitation and durability, mitigated through optimised strains and curing conditions.	High microbial culture costs, reduced through bio-engineering and scale-up.	Limited workflows for adoption, addressed through prefabricated blocks and pilot projects	Lack of infrastructure for cultivation, mitigated by modular bioreactor systems.	Absence in standards and codes, addressed by microbial materials test protocols.	Unclear ecological impacts, mitigated by biosafety assessments.	Lab-scale: ~2.2 mg CO_2/g of hydrogel (in 30 days); up to ~26 mg CO_2/g (over 400 days); not yet scalable to concrete [71]
Carbon capture integration in cement (CCS/CCUS, DAC)	Integration challenges with cement kilns, mitigated by advanced solvents and oxy-fuel retrofits.	Very high capital and operating costs, reduced by tax credits, CfDs, and AMCs.	Difficult integration into process flows, addressed by retrofit protocols and hybrid utilization.	Lack of pipelines and storage hubs, mitigated by regional clusters and CO_2 transport networks.	Misalignment with material standards, addressed by linking CCS policies to utilization pathways.	Performance concerns for storage, addressed by rigorous MRV (Monitoring, Reporting, and Verification) and long-term monitoring.	60%–90% cement plant emission reduction; > 300 kg CO_2/t cement captured (depending on efficiency) [24]

Economic barriers are compounded by the current energy crisis in contradictory ways. On one hand, the higher energy cost environment reduces the relative price premium of lower-energy-intensity alternatives such as geopolymers and MgO cements, making the business case more favourable. On the other hand, the capital costs of retrofitting ACC infrastructure into existing precast facilities remain substantial, and the limited industrial CO_2 supply networks required for ACC at scale represent a significant infrastructure investment. Jouamai et al. (2025) note that the absence of mandatory embodied carbon standards for investors — discussed further in section 1.3.2 — suppresses the market signal that would otherwise drive capital toward lower-carbon alternatives.

Implementation barriers include the fragmentation of certification and testing standards across jurisdictions. No harmonised international standard currently governs the characterisation of CO_2 sequestration in cementitious materials, creating market uncertainty for specifiers and clients. The limited availability of experienced contractors and supply chain actors capable of handling geopolymer or ACC systems at scale further constrains deployment beyond pilot projects.

Policy and regulatory barriers are closely intertwined with the embodied carbon disclosure gap addressed in section 1.3.2. The absence of binding quantitative limits on embodied carbon intensity in the majority of EU Member States — and virtually all other jurisdictions globally — means that the competitive advantage of sequestering materials is not systematically captured in procurement specifications or investment criteria.

Infrastructural barriers centre on the limited availability of industrial-grade CO_2 supply networks for ACC, which requires concentrated CO_2 typically at 10–100% concentration. The current industrial CO_2 market is fragmented, with supply dominated by food-grade applications and geographically concentrated near large point sources. Environmental barriers include residual uncertainties around the long-term permanence of mineralised CO_2 under thermomechanical cycling and freeze-thaw conditions, and the potential for leaching of activator compounds in AAM systems. Social barriers — including specifier inertia, client risk aversion, and limited awareness among built environment professionals — are cross-cutting and particularly difficult to address through regulatory intervention alone.

The energy crisis may nonetheless act as a catalyst for accelerating deployment: when the economic advantage of low-energy-intensity materials becomes self-evident through market price signals, institutional and regulatory barriers may be overcome more readily. China's expansion of its national ETS to the cement sector and the EU's CBAM both create emerging market incentives that, combined with the current fossil fuel price environment, may accelerate this transition.

1.3.2. Embodied Carbon Regulation and the EPBD 2024

The revised Energy Performance of Buildings Directive, published as EU 2024/1275 and entering into force on 28 May 2024 (EPBD, 2024), constitutes the most far-reaching regulatory intervention on building-sector carbon to date. It mandates whole-life carbon (WLC) assessments for all new buildings, using harmonised methodologies aligned with EN 15978 and the Level(s) indicator framework. Life-cycle global warming potential (GWP) must be calculated and disclosed for all new buildings exceeding 1,000 m² from 2028, and for all new buildings from 2030. In December 2025, the European Commission reinforced this framework through Delegated Regulation C(2025) 8723, establishing a common EU methodology for calculating life-cycle GWP (European Commission, 2025).

The technical backbone of this mandate is EN 15978:2011 (and its forthcoming revision under CEN/TC 350), which defines the system boundary for whole-life carbon assessment across four life-cycle stages: product and construction (modules A1–A5), use and maintenance (B1–B7), end of life (C1–C4), and beyond the system boundary (module D, covering reuse and recycling credits). The Level(s) indicator 1.2 operationalises this standard for buildings policy, requiring that GWP be expressed in kg CO_2 equivalent per square metre of net floor area per year. A critical methodological implication for the materials covered in this paper is that modules A1–A3 — encompassing raw material extraction, transport, and manufacturing — are precisely where embodied carbon reductions from carbon-sequestering cementitious materials are realised. Furthermore, module D allows for the attribution of carbonation-based CO_2 uptake during the use phase and after end-of-life crushing, a credit that is systematically excluded from current national greenhouse gas inventories but is explicitly recognised under EN 15978. The Delegated Regulation C(2025) 8723 clarifies that Member States must require this full system boundary from 2028 onwards, removing the current flexibility that has allowed practitioners to report only modules A1–A5, thereby understating embodied carbon and obscuring the comparative advantage of sequestering materials.

Embodied carbon is estimated to account for 10–25% of the total carbon footprint of current buildings, rising to approximately 400% of operational emissions in near-zero energy buildings (Pacheco-Torgal et al., 2013). Gauch et al. (2023) confirm substantial trade-offs between embodied carbon and construction cost, while BUILD UP (2025) estimates that a 40% reduction in embodied carbon can lower construction costs by nearly 10%. Chen et al. (2023) found that low-carbon cementitious binders offer embodied carbon reduction potentials 64.9% higher than supplementary cementitious materials, and the OECD (2019) projects that demand for all construction materials will double by 2060. Achieving a carbon-neutral or carbon-negative construction sector by mid-century therefore depends critically on the large-scale substitution of conventional Portland cement with the five material classes described in this paper.

A critical weakness of the EPBD 2024 framework, however, is that it imposes disclosure without binding quantitative limits on embodied carbon intensity. The experience of early-mover Member States reveals both the potential and the limits of a purely voluntary approach to limit-setting. Denmark introduced mandatory embodied carbon limits in its Building Regulation 2023 (BR23), capping life-cycle GWP at 12 kg $CO_2eq/m^2/year$ for new buildings — a threshold that already incentivises the substitution of conventional cement with lower-carbon alternatives. The Netherlands adopted a similar mandatory GWP limit of 1.0 tonne CO_2eq/m^2 over 50 years under the Milieu Prestatie Gebouwen (MPG) instrument. Finland has embedded embodied carbon targets within its national building code since 2025. By contrast, the majority of Member States remain at the disclosure-only stage, with no quantitative limit values adopted or proposed. Table 3 summarises the current state of implementation across selected Member States.

Table 3. Embodied carbon regulatory status in selected EU Member States BUILD UP (2025); European Commission (2025).

Member State	Instrument	Quantitative Limit	Status (2026)
Denmark	BR23 Building Regulation	12 kg $CO_2eq/m^2/year$	Mandatory limit in force
Netherlands	Milieu Prestatie Gebouwen (MPG)	1.0 t CO_2eq/m^2 over 50 years	Mandatory limit in force
Finland	National Building Code 2025	Phased limits from 2025; full limit by 2030	Mandatory limits being phased in
France	RE2020 regulation	Iconstruction limit (tightening in steps to 2031)	Mandatory limit in force; tightening schedule set
Germany	QNG (Sustainable Building certificate)	Voluntary GWP threshold for subsidy eligibility	Voluntary; disclosure only otherwise
Portugal	EPBD 2024 transposition (draft)	No quantitative limit proposed	Disclosure-only; transposition in progress
Spain / Italy / Poland	EPBD 2024 transposition (early stage)	No quantitative limit proposed	Disclosure-only trajectory

The fragmentation evident in Table 3 carries important market consequences. Where mandatory limits are in force, procurement specifications and green finance criteria are already beginning to differentiate materials on the basis of embodied carbon intensity. Where disclosure-only regimes prevail, the competitive signal to specifiers and investors remains absent. This regulatory unevenness creates a risk of carbon leakage within the single market: construction projects in disclosure-only jurisdictions may continue to rely on conventional high-carbon cement, while neighbouring markets with binding limits absorb the available supply of lower-carbon alternatives. The European Commission's forthcoming review of the Delegated Regulation, scheduled for 2027, is expected to

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include proposals for EU-wide mandatory GWP limits — a development that would fundamentally reshape demand for all five material classes described in this paper.

The disclosure gap in the real estate investment sector compounds this regulatory shortcoming. Weinfeld et al. (2023) demonstrated that embodied carbon disclosures by German institutional real estate investors remain scarce and of limited quality — a finding consistent with the broader evidence from GRESB's annual benchmarking surveys, which show that embodied carbon is reported by around 31% of participating real estate funds globally (GRESB, 2024). TCFD-aligned climate risk disclosures by institutional real estate investors similarly focus overwhelmingly on operational carbon and physical climate risk, with embodied carbon systematically absent from Scope 3 supply chain accounting (TCFD, 2023). This invisibility in investment reporting perpetuates the mispricing of embodied carbon risk and suppresses the flow of capital toward low-carbon construction materials. The integration of mandatory embodied carbon disclosure into EU Sustainable Finance Disclosure Regulation (SFDR) principal adverse impact indicators — currently under review by the European Supervisory Authorities — would represent the most direct regulatory pathway to closing this gap.

A further dimension of regulatory complexity arises from the interaction between the EPBD 2024 embodied carbon mandate and the EU Taxonomy Regulation (EU 2020/852). The Taxonomy's Technical Screening Criteria for the "construction of new buildings" activity already require a life-cycle GWP disclosure as a condition of substantial contribution to climate change mitigation. However, the Taxonomy does not yet impose a mandatory GWP limit for new construction to qualify as "green" — it currently requires only that buildings meet national Nearly Zero Energy Building (NZEB) standards and disclose their life-cycle GWP. This misalignment between the EPBD 2024 (which mandates disclosure and moves toward limits) and the Taxonomy (which links green finance eligibility to energy performance rather than embodied carbon intensity) creates a significant policy incoherence. Buildings financed as EU Taxonomy-aligned green assets may nonetheless have high embodied carbon footprints if constructed with conventional cement — an outcome that undermines the integrity of the sustainable finance framework. The five classes of carbon-sequestering cementitious materials described in this paper could be instrumental in enabling new construction to simultaneously satisfy NZEB energy standards and achieve low or negative embodied carbon, thereby bridging this gap. Ensuring that the forthcoming revision of the Taxonomy Technical Screening Criteria introduces a meaningful GWP intensity threshold — set at a level that incentivises the substitution of conventional cement — is therefore a regulatory priority of the first order.

1.4. Conclusions

The convergence of the 2026 Strait of Hormuz energy crisis and the accelerating trajectory of global warming has created an unprecedented strategic imperative for the construction sector. This paper reviews recent literature on five classes of cementitious construction materials with carbon sequestration capacity: accelerated carbonation curing systems, geopolymers and alkali-activated materials, recycled cement from C&D waste, biochar-modified materials, and reactive MgO cements. Their strategic relevance has been substantially amplified by the current energy crisis, as their lower energy intensity in production makes them simultaneously more competitive on cost grounds and more attractive from a decarbonisation perspective.

The principal systemic barriers to deployment — technical heterogeneity, fragmented certification standards, limited industrial CO_2 supply networks, and the absence of binding embodied carbon standards for investors — remain largely unresolved, though the energy crisis creates new economic incentives that may accelerate market uptake independently of regulatory intervention.

On the regulatory side, EPBD 2024 (EU 2024/1275) and the December 2025 Delegated Regulation C(2025) 8723 represent the most significant institutional step forward to date in mandating whole-life carbon assessment of buildings. However, as evidenced by Weinfeld et al. (2023), voluntary disclosure frameworks have demonstrably failed to produce meaningful transparency in embodied carbon reporting. The critical policy gap that remains is the absence of mandatory embodied carbon disclosure requirements for real estate investors across the EU and globally. Without binding quantitative limits on embodied carbon intensity — analogous to operational energy performance certificates — the market signal necessary to drive large-scale adoption of the five material classes described in this paper will remain insufficient.

The EU's Carbon Border Adjustment Mechanism, together with China's expansion of its national ETS to the cement sector, create emerging market incentives that may accelerate this transition, particularly when combined with the competitive cost advantage conferred by the current fossil fuel price environment. In sum, this paper establishes that carbon-sequestering cementitious construction materials are no longer a niche academic proposition but a portfolio of solutions whose time has come.

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