

Brief Report

Not peer-reviewed version

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

[F. Pacheco-Torgal](#)*

Posted Date: 20 April 2026

doi: 10.20944/preprints202604.0790.v2

Keywords: energy crisis; CO₂ sequestration; embodied carbon; cementitious materials; EPBD; carbon pricing



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Brief Report

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

F. Pacheco-Torgal

C-TAC Research Centre, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal;
torgal@civil.uminho.pt

Abstract

Five classes of cementitious construction materials — accelerated carbonation curing (ACC) systems, geopolymers and alkali-activated materials (AAMs), recycled cement from construction and demolition waste, biochar-modified composites, and reactive magnesia cements — offer the dual capacity to sequester CO₂ while substantially reducing energy consumption relative to ordinary Portland cement (OPC). This paper provides an updated scientific review of each class, drawing on literature published through early 2026, and maps their comparative strategic positioning across three dimensions: energy cost advantage, potential sequestration scale, and current deployment readiness. The convergence of the 2026 Strait of Hormuz energy crisis — which has raised construction material production costs by up to 30% — with the accelerating trajectory of global warming creates an unprecedented economic and environmental imperative for this materials portfolio. Their lower energy intensity in production makes them simultaneously more cost-competitive and more aligned with decarbonisation goals precisely when these incentives are most powerful. The paper also examines systemic barriers to large-scale deployment and evaluates the regulatory landscape, focusing on the revised EU Energy Performance of Buildings Directive (EPBD 2024, EU 2024/1275), the EU Taxonomy Regulation, and the persistent absence of mandatory embodied carbon disclosure requirements for real estate investors. The analysis identifies recycled cement and reactive MgO cement as occupying the strongest strategic position when energy cost advantage and sequestration scale are considered jointly, while ACC offers the clearest near-term deployment pathway given its compatibility with existing industrial infrastructure.

Keywords: energy crisis; CO₂ sequestration; embodied carbon; cementitious materials; EPBD; carbon pricing

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

The energy shock that began when military conflict effectively closed the Strait of Hormuz to commercial shipping in early March 2026 has created the most acute test of global construction economics in a generation. Brent crude oil prices surpassed \$100 per barrel for the first time in four years, reaching a peak of \$126 per barrel. The International Energy Agency characterised the closure as the greatest global energy security challenge in history and the largest single 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 alongside approximately 20% of global liquefied natural gas trade, primarily from Qatar. The cascading effects on building material production costs have been rapid and severe: aluminium, plastics, methanol, and petrochemicals have all registered sharp price increases, and European construction and chemical

sectors have already reported cost surcharges of up to 30% to offset surging electricity and feedstock costs.

These price pressures fall most heavily on conventional construction materials — cement, steel, and synthetic products — which are highly energy-intensive and therefore highly sensitive to fossil fuel price fluctuations. This sensitivity is not incidental: the calcination of limestone to produce Portland cement clinker alone requires temperatures of approximately 1450 °C, making conventional cement production one of the most thermally intensive industrial processes in the global economy. The current energy crisis makes visible, through price signals, what life-cycle assessments have long demonstrated in carbon accounting: conventional construction materials carry enormous embedded energy costs that have been artificially suppressed by historically cheap fossil fuels.

At the same time, the scientific case for urgent action on atmospheric CO₂ has never been stronger. During the early 18th century, coinciding with the onset of the Industrial Revolution, atmospheric CO₂ concentration stood at 280 ppm. The World Meteorological Organization reported that the globally averaged CO₂ 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 that rising seas, ocean acidification, and extreme weather would continue for at least a century (Clayton, 2001). This makes the engineered removal of CO₂ from the atmosphere an imperative rather than an option (Hansen et al., 2017), and one of the Grand Challenges of Engineering (Mote et al., 2016).

The most prominent technological approach to atmospheric CO₂ removal — direct air capture (DAC) — illustrates the scale of the challenge. In May 2024, Climeworks inaugurated its Mammoth facility in Iceland, designed to capture up to 36,000 tonnes of CO₂ per year. Yet actual capture in 2024 totalled only approximately 105 tonnes, exposing the vast gap between design ambition and operational reality (Barnard, 2025). The comparison with cementitious sequestration is instructive but must be made carefully: DAC removes CO₂ directly from the atmosphere, whereas cementitious materials primarily sequester process CO₂ or prevent its release during manufacture, with some classes also absorbing atmospheric CO₂ over their service life. These are complementary rather than competing mechanisms, and together they suggest that the construction sector can contribute to negative emissions at a scale that centralised DAC cannot currently approach. Annual removal of between 3,500 and 9,800 million tonnes of carbon will be required over the next 30 years (TE, 2023a); cementitious sequestration materials must form a core part of that portfolio.

The economic context also creates a new opening for carbon pricing instruments. There are currently two principal market-based instruments for reducing CO₂ 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 strengthen the case for carbon pricing by making the full economic costs of fossil fuel dependence visible through price shocks. Global carbon pricing revenues exceeded \$100 billion for the first time in 2024, with around 80 instruments — 43 carbon taxes and 37 ETSs — now covering 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), and the EU's Carbon Border Adjustment Mechanism will impose fees on the CO₂ content of imported cement and steel — creating incentives for low-carbon construction materials at precisely the moment when energy costs make them economically competitive.

It is against this dual backdrop — the steepest fossil fuel price shock in recent memory and the most acute atmospheric CO₂ levels in human history — that this paper examines five classes of cementitious construction materials with carbon sequestration capacity. The analysis proceeds in three stages: a scientific review of each material class and its sequestration potential (Section 2), an examination of systemic barriers to deployment and their interaction with the current energy crisis (Section 3), and a critical evaluation of the regulatory framework (Section 4). The paper argues that

these materials are no longer a niche academic proposition but a portfolio of solutions whose time, both economically and environmentally, has unambiguously arrived.

2. CO₂ Sequestration Through Cementitious Construction Materials

2.1. Natural Carbonation as a Passive Carbon Sink

Before examining engineered sequestration approaches, it is essential to acknowledge the scale of passive CO₂ uptake that already occurs through the natural carbonation of cement-based materials. 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 CO₂ emissions over the same period. A subsequent update by Huang et al. (2023) estimated accumulated global CO₂ uptake from 1930 to 2021 at 22.9 Gt CO₂. The most comprehensive analysis to date — by Niu et al. (2025), covering 163 countries and regions with 58,517 activity data points — extended this accounting to 2024 and projected global CO₂ uptake by cement carbonation at approximately 0.86 Gt CO₂ per 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 CO₂/year in 2023. The carbonation of cement-based materials is therefore a substantial and growing carbon sink whose significance is systematically underestimated in national greenhouse gas inventories.

A critical limitation of natural carbonation, however, is timescale. The process unfolds over decades as atmospheric CO₂ diffuses slowly through the concrete matrix, reacting with calcium hydroxide and calcium silicate hydrate to form stable carbonates. This means that natural carbonation cannot be counted as a near-term mitigation measure — it is a long-term accounting credit that accrues over a building's service life and beyond. The engineered approaches discussed in sections 2.2 to 2.6 are distinguished precisely by their ability to accelerate and amplify this process, achieving significant sequestration during manufacturing rather than waiting for decades of passive exposure. Furthermore, natural carbonation carries a structural penalty: reduction of concrete pH promotes reinforcement corrosion, a durability problem that accelerated carbonation curing is specifically designed to avoid by mineralising CO₂ into stable calcium silicate hydrate phases before the reinforcement is embedded.

2.2. Accelerated Carbonation Curing

Accelerated carbonation curing (ACC) — in which cement products are exposed to elevated CO₂ 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, while Xie et al. (2025) provide a mechanistic review demonstrating that ACC simultaneously sequesters CO₂ and improves mechanical properties and durability. Liu et al. (2025) further systematise the mechanisms, techniques, and precursor materials applicable to enforced carbonation for low-carbon concrete.

A particularly significant contribution comes from Fu et al. (2024), who developed a novel approach in which CO₂ is injected into a cement suspension that is subsequently used to manufacture concrete. By converting the carbonation reaction from a diffusion-controlled surface process into an aqueous ionic reaction distributed throughout the cement matrix, this method achieves CO₂ sequestration efficiency of up to 45% while maintaining uncompromised concrete strength. The approach is technically simple and therefore amenable to rapid industrial adoption — a decisive advantage over approaches that require fundamentally new manufacturing infrastructure.

Machine learning is now being applied to optimise ACC systematically. Sun et al. (2025) demonstrate that data-driven models can accurately predict CO₂ sequestration in cementitious materials as a function of mix composition and curing conditions, enabling the computational design of mixtures that maximise carbon uptake. A 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.

The pre-curing approach using sodium bicarbonate disclosed by Stefaniuk et al. (2023) addresses the durability concern directly, enabling CO₂ to be permanently mineralised into calcium-silicate-hydrate without compromising reinforcement protection. This work establishes a pathway to permanent mineralisation that is structurally safe — a prerequisite for any ACC system intended for reinforced concrete applications at scale.

In the context of the current energy crisis, ACC's energy profile is both its strength and its limitation. Because it does not eliminate calcination — the most energy-intensive step in cement production — it does not offer the same energy cost advantage as geopolymers or recycled cement. Its strategic value lies instead in its ability to sequester substantial CO₂ during an otherwise standard manufacturing step, with minimal additional energy input, at a deployment readiness level (TRL 6–8) that no other class in this review can match.

2.3. Geopolymers and Alkali-Activated Materials

Geopolymers and alkali-activated materials (AAMs) represent an entirely distinct class of construction binder with significant CO₂ sequestration potential and substantially lower embodied energy than Portland cement. Their defining characteristic is the absence of limestone calcination: instead of heating calcium carbonate to 1450 °C to produce clinker, geopolymers are synthesised by alkali-activating aluminosilicate precursors — typically industrial by-products such as fly ash from coal combustion or ground granulated blast furnace slag from steel production — at ambient or modestly elevated temperatures. This elimination of the calcination step is the primary source of their environmental advantage. Life-cycle assessment studies consistently report CO₂ emission reductions of 40–80% relative to OPC (Kriven et al., 2024). In a high-energy-price environment, the energy cost savings are direct and immediate.

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. Crucially, they also identified that even modest increases in chemical admixture content can significantly offset these environmental gains — a finding with direct implications for mix design optimisation under real-world conditions. It is not sufficient to replace clinker with fly ash and assume the benefit is secure: activator chemistry must be optimised alongside precursor selection.

The deliberate integration of CO₂ into geopolymer systems extends their sequestration potential beyond the passive emissions savings. Sahoo et al. (2024) demonstrated that accelerated carbon curing 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 in reinforced applications. Ghazouani et al. (2025) introduced the approach of aerating CO₂ 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 CO₂ 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 supercritical CO₂ curing applied 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 (Podnar et al., 2025). This approach is currently at early pilot stage but establishes a theoretical ceiling for what accelerated carbonation in geopolymer systems can achieve.

2.4. Recycled Cement from Construction and Demolition Waste

Recycled cement produced from construction and demolition (C&D) waste represents the material class with the greatest theoretical sequestration potential, but also the greatest gap between that potential and current deployment reality. Luo et al. (2024) modelled a concrete cycle centred on C&D waste recycling with integrated CO₂ sequestration and found that per tonne of recycled cement produced, CO₂ emissions are reduced by 47–94% relative to OPC. If recycled cement were to replace OPC at global scale, the potential annual CO₂ sink could reach 1.4–3.08 Gt — an order of magnitude larger than the current natural carbonation sink and equivalent to roughly 2% of total global greenhouse gas emissions.

The energy crisis context renders recycled cement doubly attractive. Because the production process avoids virgin clinker manufacture entirely — substituting demolished concrete as the raw material feedstock — it is substantially insulated from the fossil fuel price shocks that are currently driving up costs for conventional cement. The thermal processing requirements are lower, and the raw material input is a waste product that must otherwise be landfilled. In a market where production cost premiums of up to 30% are being absorbed by conventional materials, recycled cement's cost structure is increasingly competitive.

The principal technical barrier is quality control. Demolished concrete contains residual paste with variable porosity, and the heterogeneity of mixed demolition waste streams makes consistent product specification challenging. The TRL of 4–6 reflects a material that has been demonstrated at laboratory and early demonstration scale but that has not yet achieved commercial production at the quality levels required for structural specifications. Closing this gap requires investment in selective demolition practices, waste stream sorting technology, and standardised testing protocols — none of which is technically beyond reach, but all of which require coordinated policy and industry action.

2.5. Biochar-Modified Cementitious Materials

Biochar is a carbon-rich, porous material produced by heating biomass — agricultural residues, forestry waste, food processing by-products — in an oxygen-limited environment (pyrolysis). The process converts labile organic carbon that would otherwise decompose and release CO₂ into a recalcitrant form that is stable over centuries. When biochar is incorporated into cementitious systems, this stabilised carbon is effectively locked into the built environment for the life of the structure.

The sequestration mechanism in biochar-modified concretes operates through two pathways. First, the biochar itself represents sequestered carbon: its porous surface chemistry retains CO₂ adsorbed during carbonation exposure, and its high specific surface area creates additional sites for carbonate mineralisation. Second, biochar's internal pore network modifies concrete microstructure in ways that accelerate the rate of carbonation front penetration — the biochar acts as a CO₂ transport highway through the matrix, exposing more calcium-bearing phases to reactive CO₂. The net result is both a material with sequestered carbon embedded in its structure and a matrix that is more reactive toward atmospheric and process CO₂ than equivalent mixes without biochar.

Zhou et al. (2025) identify conditions under which biochar-modified materials achieve net-negative carbon footprints: approximately 30 wt% aggregate substitution under CO₂ curing delivers 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 CO₂eq per tonne is achievable. Biochar is the only material class in this review capable of achieving a net-negative carbon footprint — a distinction that will become commercially significant as mandatory embodied carbon limits tighten. The use of agricultural and forestry residues as feedstocks is also relevant to the energy crisis context: biomass-derived materials are insulated from fossil fuel price shocks in a way that energy-intensive conventional materials are not.

The principal limitation is TRL. Biochar-modified construction materials remain largely at laboratory scale, with no harmonised characterisation methods for construction-grade biochar and significant feedstock heterogeneity across regions. Scaling the supply chain for agricultural biochar

to construction volumes is a non-trivial logistical and agronomic challenge that is not yet well mapped in the literature.

2.6. Reactive MgO Cement

Reactive magnesia (MgO) cements are fundamentally different from Portland cement in their binding mechanism: rather than relying on calcium silicate hydrate gel formation, they bind through the carbonation of MgO to form hydrated magnesium carbonates as their primary binding phase. This means that carbonation is not a durability problem for reactive MgO cements, as it is for Portland cement, but the essential mechanism of strength gain. Each kilogram of carbonated reactive MgO cement sequesters up to 0.78 kg of CO₂ – one of the highest per-unit sequestration efficiencies in this review.

Tan et al. (2024), through a comprehensive life cycle assessment, demonstrate that using MgO derived from salt lake magnesium residues reduces CO₂ emissions by over 60% relative to conventional MgO production, and that carbonated reactive MgO cement achieves compressive strengths up to three times higher than OPC. The energy economics are particularly relevant in the current crisis context: the calcination temperature for reactive MgO production is 700–1000 °C, substantially lower than the 1450 °C required for Portland cement clinker, producing significant fuel savings at a moment when fuel prices are at elevated levels.

The durability case for reactive MgO cement in reinforced concrete requires further investigation: because the binding mechanism depends on sustained CO₂ availability, performance in sealed or low-permeability environments may differ from that in conventionally cured specimens. The TRL of 5–7 reflects genuine pilot-scale demonstrations but indicates that structural-scale performance data under field conditions remains limited.

2.7. Strategic Positioning: A Comparative Framework

Table 1 provides a comparative overview of the five material classes across the four key dimensions of CO₂ uptake, emission reduction versus OPC, energy intensity, and technology readiness. TRL values in this table follow the European Commission definition: TRL 4 corresponds to laboratory validation, TRL 6 to prototype demonstration in a relevant environment, TRL 7–8 to pilot and pre-commercial scale, and TRL 9 to full commercial deployment. The table makes clear that no single material class dominates across all four dimensions simultaneously.

Table 1. Comparative overview of five cementitious material classes with CO₂ sequestration capacity. TRL: Technology Readiness Level following European Commission definitions (TRL 4 = laboratory validation; TRL 6 = prototype in relevant environment; TRL 7–8 = pilot/pre-commercial; TRL 9 = commercial). All sequestration values are indicative and subject to mix design, curing conditions, and precursor variability.

Material class	CO ₂ uptake (indicative)	CO ₂ reduction vs OPC (%)	Energy intensity vs OPC	TRL	Key reference(s)
Accelerated carbonation curing (ACC)	Up to 45% sequestration efficiency	20–40%	Similar to OPC; no additional calcination	TRL 6–8	Wang & Fan (2025); Fu et al. (2024)
Geopolymers / alkali-activated	Up to 12.7% CO ₂ uptake by mass	40–80%	Significantly lower (no)	TRL 5–7	Kriven et al. (2024); Tushar et al. (2025)

materials (AAMs)			limestone calcination)		
Recycled cement (C&D waste)	Potential 1.4–3.08 Gt CO ₂ /year at global scale	47–94%	Substantially lower (avoids virgin clinker)	TRL 4–6	Luo et al. (2024)
Biochar-modified cementitious materials	541–980 kg CO ₂ eq/t at 5% blending	Net-negative achievable at ~30 wt%	Lower (biomass-derived; fossil-fuel insulated)	TRL 4–6	Zhou et al. (2025)
Reactive MgO cement (CRMC)	Up to 0.78 kg CO ₂ /kg MgO	>60% (salt lake MgO source)	Lower calcination temp (700–1000 °C vs 1450 °C)	TRL 5–7	Tan et al. (2024)

Figure 1 maps these five classes across three strategic axes — energy cost advantage (reflecting % reduction in energy intensity versus OPC), sequestration scale (a normalised index of CO₂ uptake potential), and deployment readiness (represented by bubble size proportional to TRL midpoint). The figure makes visible a strategic tension that the tabular data alone obscures: the materials with the greatest combined energy advantage and sequestration scale — recycled cement and reactive MgO cement — occupy the middle range of deployment readiness, while the most deployment-ready material, ACC, offers more modest energy cost advantages. This is the central portfolio challenge for the construction sector: the strongest long-term options are not yet the easiest near-term choices.

[Figure 1: Strategic positioning matrix — insert from interactive visualisation]

Figure 1. Strategic positioning of five carbon-sequestering cementitious material classes by energy cost advantage (x-axis, % reduction in energy intensity versus OPC), sequestration scale (y-axis, normalised index of CO₂ uptake potential), and deployment readiness (bubble diameter proportional to TRL midpoint). The dashed zone denotes the strategic sweet spot where high energy advantage and high sequestration scale converge.

If the five material classes were deployed at the maximum scale that current technical literature projects to be achievable, the combined annual CO₂ sink could plausibly reach 2–5 Gt CO₂/year — equivalent to 5–12% of current global greenhouse gas emissions. Recycled cement alone accounts for the largest share of this theoretical maximum (1.4–3.08 Gt/year), underscoring the importance of accelerating its TRL trajectory despite the current barriers to C&D waste supply chain development.

3. Barriers to Large-Scale Deployment

Despite the compelling scientific evidence reviewed in Section 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: technical, economic, implementation, policy and regulatory, environmental, infrastructural, and cross-cutting social factors. Table 2 maps these barriers across the five material classes, enabling both within-class and cross-cutting analysis.

Table 2. Comparative barrier matrix for five carbon-sequestering cementitious material classes across key deployment domains. Source: adapted from Jouamai et al. (2025) with additional synthesis from reviewed literature.

Material class	Technical	Economic	Implementation	Policy / regulatory	Environmental
ACC	CO ₂ supply availability; moisture sensitivity; late-stage pH reduction	ACC infrastructure retrofit costs; limited industrial CO ₂ networks	No harmonised standard for CO ₂ sequestration measurement	Sequestration credits excluded from most GHG inventories	Durability under thermomechanical cycling; reinforcement corrosion risk
Geopolymers / AAMs	Precursor variability; limited long-term field durability data	Higher activator costs partially offset energy savings	Absence of international standards; contractor unfamiliarity	No binding embodied carbon limits in most Member States	Activator leaching potential in AAM systems
Recycled cement	Demolition waste quality control; residual paste porosity penalty	C&D waste collection infrastructure investment required	Fragmented demolition waste supply chains across jurisdictions	Embodied carbon not captured in investor disclosure frameworks	Contaminant risk in mixed demolition waste streams
Biochar-modified	Feedstock heterogeneity; no harmonised characterisation methods	Feedstock cost and availability vary widely by region	Limited supply chain for construction-grade biochar	No net-negative carbon accounting framework for procurement	Long-term CO ₂ permanence under freeze-thaw conditions uncertain
Reactive MgO cement	Humidity and CO ₂ concentration sensitivity; limited	MgO feedstock supply concentrated in China;	No established certification pathway in EU or North America	Sequestration mechanism not recognised	Salt lake extraction impacts require full LCA accounting

	structural-scale data	price exposure		in current EN 15978 modules	
--	-----------------------	----------------	--	-----------------------------	--

Technical barriers are the most varied across the five classes. For ACC, the principal constraints are the limited industrial availability of concentrated CO₂ streams, the sensitivity of carbonation kinetics to moisture content and mix design, and the durability concerns associated with late-stage natural carbonation promoting reinforcement corrosion – concerns that the pre-curing approaches of Stefaniuk et al. (2023) and Fu et al. (2024) are beginning to resolve. 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 absence of standardised mix design protocols, and limited long-term field durability data. For biochar-modified materials, feedstock heterogeneity and the lack of harmonised characterisation methods limit reproducibility. For reactive MgO cements, sensitivity of carbonation efficiency to curing humidity and CO₂ concentration, combined with limited structural-scale performance data, remains a constraint. Recycled cement faces barriers around demolition waste quality control and the mechanical performance penalty associated with residual paste porosity.

Economic barriers are interacting with the 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 without any policy intervention. On the other hand, the capital costs of retrofitting ACC infrastructure into existing precast facilities remain substantial, and the limited industrial CO₂ supply networks required for ACC at scale represent significant investment requirements that are competing for capital with other energy crisis response measures.

Implementation barriers are dominated by the fragmentation of certification and testing standards across jurisdictions. No harmonised international standard currently governs the characterisation of CO₂ 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. These are not insurmountable barriers – standards development is an established process – but it is slow, and the urgency of the climate context means that the pace of standards development is itself a barrier.

Infrastructural barriers centre on the limited availability of industrial-grade CO₂ supply networks for ACC, which requires concentrated CO₂ typically at 10–100% concentration. The current industrial CO₂ market is fragmented, with supply dominated by food-grade applications and geographically concentrated near large point sources. The geographic mismatch between CO₂ supply and cement production locations adds logistical cost and complexity.

Policy and regulatory barriers are closely intertwined with the embodied carbon disclosure gap addressed in Section 4. 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. Without a regulatory signal that prices embodied carbon, the market cannot reward the materials that reduce it most effectively.

Social barriers – specifier inertia, client risk aversion, and limited awareness among built environment professionals – are cross-cutting and particularly difficult to address through regulation alone. They tend to diminish as successful projects accumulate and as early-mover firms develop competitive advantage in lower-carbon procurement. The energy crisis may, paradoxically, accelerate this cultural shift: when the cost advantage of low-energy-intensity materials becomes self-evident through market price signals, the institutional and regulatory barriers to adoption may be overcome more readily than through any amount of top-down policy intervention.

4. Embodied Carbon Regulation: The EPBD, the Taxonomy, and the Investment Gap

4.1. The EPBD 2024 Framework

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, 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). 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 CO₂ uptake during the use phase and after end-of-life crushing – a credit that is systematically excluded from current national greenhouse gas inventories but 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 flexibility that has allowed practitioners to report only modules A1–A5 and thereby understate embodied carbon.

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). Research by Gauch et al. (2023) highlights significant tensions between minimising embodied carbon and managing construction expenditure, while BUILD UP (2025) estimates that achieving a 40% cut in embodied carbon could reduce construction costs by close to 10% – suggesting that embodied carbon reduction and cost reduction are more complementary than they are in conflict. A systematic review by Chen et al. (2023) demonstrated that low-carbon cementitious binders outperform supplementary cementitious materials in embodied carbon reduction by roughly 64.9%.

Table 3 summarises the current state of embodied carbon regulation across selected EU Member States. The contrast between early movers and the majority of Member States is stark. Denmark introduced mandatory embodied carbon limits in its Building Regulation 2023 (BR23), capping life-cycle GWP at 12 kg CO₂eq/m²/year – a threshold that already incentivises the substitution of conventional cement with lower-carbon alternatives. The Netherlands adopted a mandatory GWP limit of 1.0 tonne CO₂eq/m² over 50 years. Finland has embedded embodied carbon targets within its national building code since 2025. France's RE2020 regulation imposes limits that tighten in steps through 2031. By contrast, the majority of Member States – including Portugal, Spain, Italy, and Poland – remain at the disclosure-only stage, with no quantitative limit values adopted or proposed.

Table 3. Embodied carbon regulatory status in selected EU Member States as of 2026. Sources: BUILD UP (2025); European Commission (2025).

Member State	Instrument	Quantitative limit	Status (2026)
Denmark	BR23 Building Regulation	12 kg CO ₂ eq/m ² /year	Mandatory limit in force

Netherlands	Milieu Prestatie Gebouwen (MPG)	1.0 t CO ₂ eq/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 significant market consequences. Where mandatory limits are in force, procurement specifications and green finance criteria are already differentiating 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 include proposals for EU-wide mandatory GWP limits — a development that would fundamentally reshape demand for all five material classes described in this paper. Setting these limits at levels that actually require the substitution of conventional cement — rather than levels that can be met through improved operational efficiency alone — is a design choice of the first order.

4.2. Misalignment with the EU Taxonomy Regulation

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 is significant. 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 that has not yet received commensurate attention in policy discussions.

4.3. *The Investment Disclosure Gap*

The most persistent systemic failure in the current framework is the invisibility of embodied carbon in real estate investment reporting. Research by Weinfeld et al. (2023) revealed that reporting on embodied carbon by German institutional real estate investors is both infrequent and of insufficient informative quality. This finding is consistent with 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) — meaning that nearly 70% of funds tracked by the world's leading real estate sustainability benchmark make no disclosure on the subject. TCFD-aligned climate risk disclosures 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 mechanism is straightforward: if investors are not required to disclose the embodied carbon of their assets, they have no financial incentive to specify lower-carbon materials in construction briefs, and developers therefore face no client pressure to substitute conventional cement. The regulatory instruments reviewed in sections 4.1 and 4.2 address the building permit and green finance eligibility dimensions of this problem, but neither instrument reaches the investment reporting chain that governs procurement decisions for the majority of commercial construction.

The most direct regulatory pathway to closing this gap would be the integration of mandatory embodied carbon disclosure into EU Sustainable Finance Disclosure Regulation (SFDR) principal adverse impact indicators, which are currently under review by the European Supervisory Authorities. Without this addition, the voluntary disclosure frameworks that have prevailed to date will continue to produce the outcome that Weinfeld et al. (2023) documented: infrequent, inconsistent reporting that is insufficient to drive capital allocation decisions. The experience of operational energy performance — where mandatory certificates transformed market behaviour rapidly and durably — should serve as the model for embodied carbon policy design.

5. 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 has reviewed 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 — and has mapped their comparative strategic positioning across three dimensions: energy cost advantage, sequestration scale, and deployment readiness.

The strategic matrix (Figure 1) reveals a fundamental tension: the materials with the greatest combined energy advantage and sequestration scale — recycled cement and reactive MgO cement — are not yet the easiest near-term choices, while the most deployment-ready option, ACC, offers more modest energy cost advantages. This is the central portfolio challenge. The appropriate policy response is not to select a single winning technology but to advance the full portfolio along complementary trajectories: ACC for near-term commercial deployment; geopolymers and MgO cements for medium-term market development; recycled cement and biochar-modified materials for long-term supply chain development and TRL advancement.

If the five material classes were deployed at the maximum scale that current technical literature projects to be achievable, the combined annual CO₂ sink could plausibly reach 2–5 Gt CO₂/year, equivalent to 5–12% of current global greenhouse gas emissions. Realising even a fraction of this

potential depends critically on resolving the systemic barriers identified in Section 3: fragmented certification standards, limited industrial CO₂ supply networks, absent binding embodied carbon limits, and the persistent invisibility of embodied carbon in investment reporting.

On the regulatory side, EPBD 2024 and the December 2025 Delegated Regulation represent the most significant institutional step forward to date. However, as evidenced by Weinfeld et al. (2023), voluntary disclosure frameworks have demonstrably failed to produce meaningful transparency in embodied carbon reporting. Three specific regulatory actions are required to close the remaining gaps. First, EU-wide mandatory GWP intensity limits must be set at levels that actually require cement substitution — not merely disclosure — when the Delegated Regulation is reviewed in 2027. Second, the EU Taxonomy Technical Screening Criteria must be revised to introduce a GWP threshold for ‘green’ building classification, eliminating the current perverse situation in which high-embodied-carbon buildings can qualify as sustainable investments. Third, mandatory embodied carbon disclosure must be integrated into SFDR principal adverse impact indicators, ensuring that the investment chain — which governs the majority of commercial construction decisions — is subject to the same transparency requirements as operational energy performance.

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 independently of regulatory action, particularly when combined with the competitive cost advantage conferred by the current fossil fuel price environment. The commercial case for carbon-sequestering cementitious materials has never been stronger. The policy case has never been clearer. The scientific case has never been better evidenced. What remains is the institutional will to close the gap between knowledge and action.

Acknowledgments: This research was supported by FCT-Fundação para Ciência e Tecnologia within the scope of the project CEECIND/00609/2018.

References

- Barnard, M. (2025). The Mammoth failure of direct air capture. *The Future is Electric*, Medium, September 2025.
- Betts, R., Jones, C., Knight, J., Keeling, R., & Kennedy, J. (2016). El Niño and a record CO₂ rise. *Nature Climate Change*, 6, 806–810.
- BUILD UP (2025). Building for the future: Driving EPBD whole-life carbon ambition across the EU. European Commission.
- Chen, S., Teng, Y., Zhang, Y., Leung, C. K., & Pan, W. (2023). Reducing embodied carbon in concrete materials: A state-of-the-art review. *Resources, Conservation and Recycling*, 188, 106653.
- Clayton, R. (2001). Editorial: Is sustainable development an oxymoron? *Trans I Chem E*, 79(Part B), 327–328.
- Climeworks (2024). Climeworks switches on world’s largest direct air capture plant, Mammoth. Press release, 8 May 2024.
- EPBD (2024). Directive (EU) 2024/1275 of the European Parliament and of the Council on the energy performance of buildings. *Official Journal of the European Union*, 8 May 2024.
- European Commission (2025). Delegated Regulation C(2025) 8723: Framework for calculating the life-cycle global warming potential of new buildings. Brussels, 16 December 2025.
- Fu, X., Guerini, A., Zampini, D., & Rotta Loria, A. F. (2024). Storing CO₂ while strengthening concrete by carbonating its cement in suspension. *Communications Materials*, 5, 109.
- Gauch, H. L., Dunant, C. F., Hawkins, W., & Serrenho, A. C. (2023). What really matters in multi-storey building design? *Applied Energy*, 333, 120585.
- Ghazouani, N. et al. (2025). Optimizing CO₂-activated alkali solutions for enhanced strength and carbon sequestration in GGBS-metakaolin geopolymer composites. *Construction and Building Materials*.
- GRESB (2024). 2024 Real Estate Assessment Results. GRESB.
- Hansen, J., Sato, M., Kharecha, P. et al. (2017). Young people’s burden: Requirement of negative CO₂ emissions. *Earth System Dynamics*.

- Huang, Z. et al. (2023). Global carbon uptake of cement carbonation accounts 1930–2021. *Earth System Science Data Discussions*, 2023, 1–28.
- Jouamai, B., Elminor, H., & Belabid, A. (2025). Challenges of carbon sequestration in construction materials – A scoping review. *Journal of Building Engineering*, Article 114349.
- Kriven, W. M., Shi, C., Provis, J. L. et al. (2024). Why geopolymers and alkali-activated materials are key components of a sustainable world. *Journal of the American Ceramic Society*, 107, 5159–5177.
- Langie, K. M. G., Tak, K., Kim, C. et al. (2022). Toward economical application of carbon capture and utilization technology with near-zero carbon emission. *Nature Communications*, 13, 7482.
- Liang et al. (2025). A comprehensive review of mineral carbonation of civil engineering materials: A bibliometric analysis. *Environmental Science & Technology*.
- Liu, J., Liu, Y., Zeng, J., & Zhuge, Y. (2025). A comprehensive review of mechanisms, techniques and precursors in enforced carbonation for low-carbon concrete. *Journal of Building Engineering*.
- Luo, J., Huang, R., Wang, J., & Zhang, Y. (2024). Carbon sequestration by preparing recycled cement, recycled aggregates, and recycled concrete from C&D wastes. *Materials*, 17(20), 5020.
- Mote, C., Dowling, J., & Zhou, J. (2016). The power of an idea: The international impacts of the Grand Challenges for Engineering. *Engineering*, 2, 4–7.
- Niu, L., Wu, S., Andrew, R. M., Shao, Z., Wang, J., & Xi, F. (2025). Global and national CO₂ uptake by cement carbonation from 1928 to 2024. *Earth System Science Data*, 17, 2231–2247.
- OECD (2019). *Global material resources outlook to 2060*. OECD Publishing, Paris.
- OECD (2025). *Effective carbon rates 2025*. OECD Publishing, Paris.
- Pacheco-Torgal, F., Faria, J., & Jalali, S. (2013). Embodied energy versus operational energy. *Materials Science Forum*, 730, 587–591.
- Pacheco-Torgal, F. et al. (2024). Carbon dioxide storage-based cementitious construction materials. Woodhead Publishing.
- Podnar, T. M., Knez, Ž., & Kravanja, G. (2025). Enhancing strength and CO₂ uptake in lignite-based fly ash geopolymer mortar through supercritical carbonation. *The Journal of Supercritical Fluids*, 225, 106695.
- Rockström, J. et al. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, 14(2), 32.
- Sahoo, P., Rao, N., & Gupta, S. et al. (2024). Carbon sequestration in earth-based alkali-activated mortar: Phase changes and performance after natural exposure. *npj Materials Sustainability*, 2, 34.
- Stefaniuk, D., Hajduczek, M., Weaver, J. C., Ulm, F. J., & Masic, A. (2023). Cementing CO₂ into CSH: A step toward concrete carbon neutrality. *PNAS Nexus*, 2(3), pgad052.
- Sun, Y., Zhang, C., Wei, Y. H. et al. (2025). Machine learning for efficient CO₂ sequestration in cementitious materials: A data-driven method. *npj Materials Sustainability*, 3, 9.
- Sun, T., Peng, R., Alrefaei, Y., Xian, X., & Wang, Y. (2025a). Influence of carbonation initiation timing on CO₂ uptake and mechanical performance of geopolymer made from ternary solid wastes. *Construction and Building Materials*, 498, 144033.
- Tan, Y., Liu, S., Achintha, M., & Mi, R. (2024). Is it possible to make magnesia-based cement environmentally friendly? *ACS Sustainable Chemistry & Engineering*, 12(46), 16869–16883.
- TCFD (2023). *2023 Status Report*. Financial Stability Board.
- TE (2023a). *The coming years will be the hottest ever*. *The Economist*, 17 May 2023.
- Tushar, Q., Bhuiyan, M. A., Abunada, Z., Lemckert, C., & Giustozzi, F. (2025). Carbon footprint and uncertainties of geopolymer concrete production: A comprehensive life cycle assessment. *Carbon*, 11(3), 55.
- Wang, L., & Fan, Y. (2025). Carbon sequestration technology in concrete: A review of mechanism, application and optimization strategy. *Journal of Building Engineering*, 102, 111862.
- WEF (2026). *Beyond oil: 9 commodities impacted by the Strait of Hormuz crisis*. World Economic Forum.
- Weinfeld, S., Wijek-Roy, G., & Booth, C. A. (2023). Embodied carbon reporting by German real estate institutional investors. *Journal of Sustainability Research*, 5(1).
- Wesseh, P. et al. (2017). Carbon taxes, industrial production, welfare and the environment. *Energy*, 123, 305–313.
- WMO (2025). *WMO Greenhouse Gas Bulletin No. 21*. World Meteorological Organization, Geneva.
- World Bank (2025). *State and Trends of Carbon Pricing 2025*. World Bank, Washington DC.

- Xi, F. et al. (2016). Substantial global carbon uptake by cement carbonation. *Nature Geoscience*, 9, 880–883.
- Xie, F., Zhou, D., & Zhang, M. (2025). Research progress on CO₂ curing of cementitious materials: A review. *Canadian Journal of Civil Engineering*, 52(6), 1045–1059.
- Zhang, Z. et al. (2017). How to improve the performance of carbon tax in China? *Journal of Cleaner Production*, 142(4), 2060–2072.
- Zhang, Z., & Huisingsh, D. (2017). Carbon dioxide storage schemes. *Journal of Cleaner Production*, 142, 1055–1064.
- Zhou, Q., Wu, D., Ye, C., Du, J., Qiu, L., Jin, M., & Wu, W. (2025). Carbon sequestration potential of biochar-modified building materials: A critical review. *Journal of Building Engineering*.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.