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Perspective

Cement and concrete as carbon sinks: Transforming a climate challenge into a carbon storage opportunity

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ABSTRACT

Cement and concrete, while traditionally recognized as one of the main contributors to anthropogenic CO_2 emissions, also have untapped capacity to serve as substantial carbon sinks. This paper provides a comprehensive perspective on how engineered mineral carbonation can transform cement-based materials into carbon storage systems. We briefly review the fundamental mechanisms of CO_2 storage in cementitious systems and highlight current limitations in understanding of reaction kinetics, end-phase regulation and performance control. The effect of CO_2 uptake on material performance is critically evaluated with respect to the fresh performance, mechanical properties and long-term durability. Emphasis is placed on the valorization of alkaline industrial residues and emerging carbonatable binders, which offer sequestration capacity and sustainable resource use. A strategic roadmap is proposed with integration of scientific innovation, regulatory alignment, and carbon accounting in the life cycle, to accelerate the adoption of carbon-storing concrete. This perspective provides a framework to advance cement and concrete as engineered carbon sinks and supports the transition to a climate-positive construction industry.

1. Introduction

Concrete is the most extensively used artificial material on Earth. The high demand for cement in making concrete has driven a significant increase in the production since its invention. The latest data from the United States Geological Survey (USGS) (Hatfield, 2025) indicated a mild decrease since 2018, but the amount remained approximately 4.15 billion tonnes (Gt) in 2023. Cement clinker production is an emissions-intensive process with an average emission of 0.58 tonnes CO_2 per tonne of Portland cement in general (International Energy Agency, 2024). Therefore, the increase in cement production was deemed to cause a rise in emissions, peaking at approximately 7.1 % and now stabilizing at about 6.4 % within fossil emissions excluding carbonation (Fig. 1a). Due to the alkalinity of cement and hydration products, CO_2 can be stored in these materials through a series of carbonation reactions that occur under CO_2 exposure with sufficient moisture. Unreacted clinker minerals, such as alite (C_3S) and belite (C_2S), can react with CO_2 to produce calcium carbonate ($CaCO_3$) and silica-alumina gel (Zajac et al., 2022). Furthermore, hydration products such as calcium hydroxide and calcium silicate hydrate (C–S–H) undergo carbonation; calcium hydroxide reacts readily to form $CaCO_3$, while C-S-H gradually decalcifies under CO_2 exposure, forming $CaCO_3$ and amorphous silica (Šavija and Luković, 2016). Additionally, aluminate phases such as monosulfate (AFm) and ettringite (AFt) can decompose and transform into carbonate-containing phases or secondary gels (Zajac et al., 2023).

The large volume of cement-based materials presents a unique opportunity for climate solutions. Natural carbonation of cement during its production and service life under ambient conditions showed an annual CO_2 uptake of 0.5 to 0.9 Gt since 2015 as estimated by some studies (Cao et al., 2020; Friedlingstein et al., 2025; Z. Huang et al., 2023), but this amount is far less than the emissions generated from its production (Fig. 1b). A recent study suggested that cement and filler materials could store >2.6 Gt of CO_2 every year, almost equivalent to the annual global CO_2 emissions from cement production (Van Roijen et al., 2025), and if aggregates and other major building materials are taken into account, the theoretical storage capacity reaches 16 Gt (Fig. 1c). The storage potential of aggregates stems from the carbonatable nature of rocks

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(Stillings et al., 2023) and the carbonation treatment of recycled aggregate adhered with paste (Villagran-Zaccardi et al., 2025).

Traditionally, the carbonation of cement and concrete was viewed as a slow passive process in nature and detrimental to the durability (Ho and Lewis, 1987). However, the emerging vision is clear that carbonation of cement concrete materials can become part of the solution to industrial emissions. It can be accelerated by enforced curing and engineered treatment. Emerging technologies, including accelerated carbonation curing, indirect mineral carbonation, and carbonate reactive binder systems, allow the capture of CO_2 in precast elements (Zhang, 2024), recycled aggregates, and construction waste (Poon et al., 2023). In addition to carbon storage in traditional Portland cement concrete, attention is also increasing to exploring the use of novel carbonatable binders from alkaline wastes like steel slag and magnesium slag whose processing status has been systematically evaluated by reviews (Liu et al., 2023; Lv et al., 2025). Moreover, magnesium based cements also show promising CO_2 adsorption capacity (Badjatya et al., 2022; Tan et al., 2024).

Despite this huge potential, most current studies have focused on optimizing adsorption efficiency and testing concrete performance at the early ages on a laboratory scale. Real-world implementation has reached <10 % of the theoretical value (Driver et al., 2024) due to technical and economic barriers in three aspects: (1) the complexity of controlling the carbonation efficiency and end-phases from mineralization of cement-based materials, and alkaline waste due to their heterogeneity in composition and microstructure (Zajac et al., 2023); (2) the high cost of the enforced carbonation curing and chemical processes (Huijgen et al., 2007; Kajaste and Hurme, 2016; Van Roijen et al., 2025) or the production of novel carbonatable binders such as magnesia cements (Walling and Provis, 2016); and (3) unaddressed durability concerns of reinforced concrete after carbonation or when using carbonated binders (Angst et al., 2019; Blackshaw et al., 2024; Li et al., 2018; Sharmilan et al., 2024).

Therefore, the successful shift from the climate challenge to a carbon storage opportunity demands deeper studies on carbonation of cement and concrete with novel cost- and eco-efficient techniques, achieved through better reaction control of its reaction and circular use of waste for value-added products after CO_2 storage. Here, we provide an overview of the carbon mineralization mechanism in cement-based materials to address the knowledge gaps in reaction control. A critical summary of the performance and cost of carbonatable cement will be followed, and the major concerns about durability will be clarified. In the last section, we offer our overall prospects for prioritized research needs to unlock the potential for carbon storage in cement and concrete.

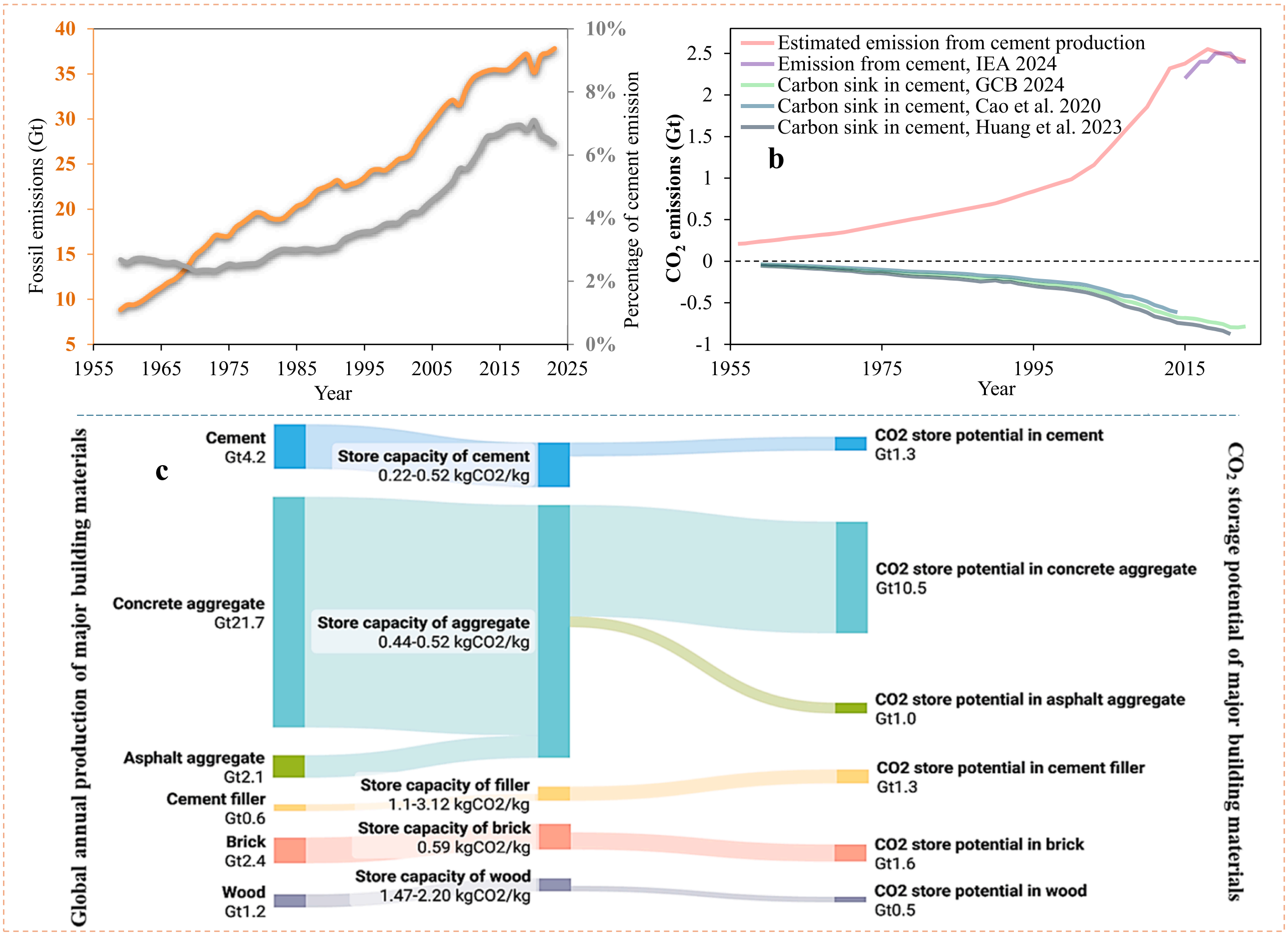

Fig. 1. Global CO_2 emissions from cement production and theoretical storage capacity of building materials. (a) Global fossil emissions with data sourced from (Friedlingstein et al., 2025) and the estimated percentage of emissions from cement production, (b) value estimated in this work with emission factor for clinker production of 0.58 g/g adopted from (International Energy Agency, 2024) and global cement production data sourced from USGS in comparison to data ranging 2015 to 2023 from (International Energy Agency, 2024) and carbon sink in cement data from Global Carbon Budget (GCB) (Friedlingstein et al., 2025), Cao et al. (Cao et al., 2020) and Huang et al.(Z. Huang et al., 2023), (c) Global production of major building materials and their theoretical CO_2 storage capacities (Van Roijen et al., 2025).

2. Scientific and technical gaps in cement-based carbon storage

2.1. Incomplete understanding of carbonation mechanisms in a complex cement system

The mineral carbonation of a cement-related system is fundamentally similar to the water-rock interactions during the natural weathering process, which involves the dissolution of minerals, precipitation of calcium carbonates along with gels, and subsequent mass diffusion to the intact inner surface (Lasaga, 1984; Coogan et al., 2016; Kelemen et al., 2019). As illustrated in Fig. 2a, these chemical processes are coupled during the carbonation of cement-based materials, so any of them could be the rate-limiting step that determines the efficiency of CO_2 storage. The controlling process could be governed by either thermodynamics or kinetics, depending on environmental conditions, the type of cementitious materials and microstructural properties. The kinetics of reaction and phase assemblage in end-products would in-turn alter the microstructure and determine the performance of carbon-stored concretes (Zajac et al., 2020a; Van Roijen et al., 2024).

Calcium carbonate, as the major precipitated products, is one of the materials found to have more than one amorphous state (Cartwright et al., 2012) and exhibits polymorphism of crystalline structures (calcite, aragonite, and vaterite), a phenomenon that has been largely studied in the realm of biomineralization (Gower, 2008). The revolution of calcium carbonates is a complex process that typically follows a non-classical nucleation and growth pathway, as highlighted by a recent study (Jin et al., 2025). The presence of multiple elements in cementitious materials (Si, Al, Fe, and S) affects the kinetics and polymorphs of calcium carbonates. Kellermeier et al. (2010) demonstrated that in solutions containing silicate ions over 1000 ppm, the formation of amorphous calcium carbonate (ACC) particles causes spontaneous silica polymerization at their vicinity, triggered by a pH drop near the surface of the ACC. This process causes the deposition of hydrated amorphous silica layers on the ACC grains, effectively suppressing further crystal growth and modifying the final particle size and morphology. Korchef (2019) demonstrated that iron ions exhibit concentration-dependent effects on calcium carbonate crystallization: At high supersaturation, they have negligible inhibitory effects, while at low supersaturation, which may induce retarding effect on the nucleation. Sulfate stabilizes the vaterite polymorph of calcium carbonate by preferentially incorporating into its structure at low concentrations (<3 mol %), which delays the transformation to calcite, while such a substitution is energetically unfavored in calcite and highly unfavorable in aragonite, thus changing the crystallization pathway of vaterite (Fernández-Díaz et al., 2010; Chong and Sheikholeslami, 2001).

The storage capacity of cementitious materials remains broadly similar, irrespective of the specific polymorph of the resulting calcium carbonate. However, the kinetics of carbonation can differ markedly to influence the efficiency of CO_2 capture. The stability of ACC and crystalline carbonates show large difference (Gebauer et al., 2008), which will, in turn, affect the long-term reliability and soundness of permanent storage. The effect of other elements on these storage aspects of real-world concrete mixes remains poorly understood, and there is a clear need for comprehensive, in-depth studies in this area.

The carbonation kinetics and reaction degree of compositions in hydration products determine the carbon storage efficiency, stability, and capacity. The major hydration product of Portland cement is C-S-H, whose structure is an amorphous state with variable Ca/Si ratios depending on the amounts of alternative siliceous binders (Lothenbach et al., 2011; L. Huang et al., 2025b), portlandite, and aluminate phases such as monosulfate and ettringite. The carbonation kinetics and storage capacity of these phases have been proven to be very different and moisture-dependent in studies using synthetic materials (Steiner et al., 2020). As summarized in Fig. 2b, while portlandite reacts readily with CO_2, C-S-H carbonation is slower with the reaction rate and adsorption capacity showing an increasing trend as the Ca/Si ratio increases; ettringite has the lowest storage capacity. However, the carbonation reaction in real cement and concrete materials is much more complex than in synthetic powdered materials because of the multiscale pore structure formed after hydration reaction. The degree of cement hydration will determine not only the microstructure but also the end products whose carbonation capacity may become weaker as the Ca/Si

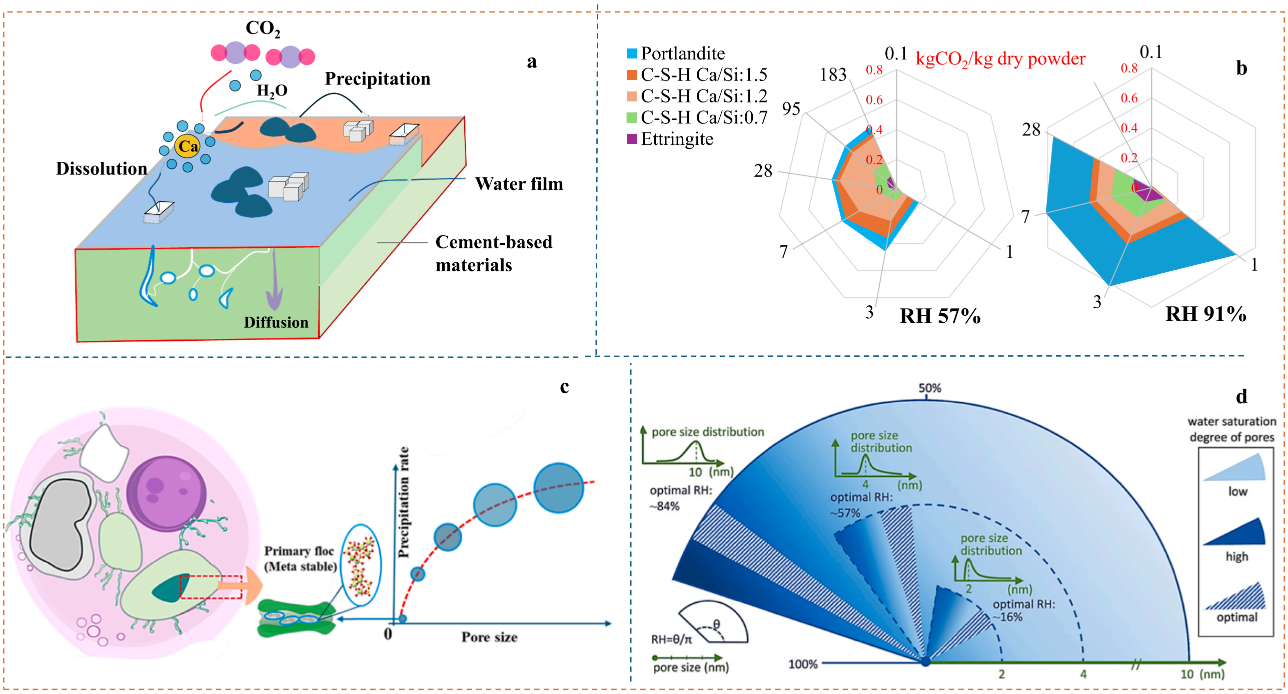

Fig. 2. Mechanisms and factors that influence CO_2 mineralization in cement-based materials. (a) Major chemical reaction processes, (b) carbonation rate and capacity of the main phases of cement products (Steiner et al., 2020), (c) Nucleation rate depending on the size of nano pores in the hydrated cement (L. Huang et al., 2025b), d– Optimum relative humidity for carbonation depending on the pore size distribution (Li et al., 2024).

ratio decreases. The sophisticated microstructure makes impact on the moisture state and distribution, especially for blended system where the nanoscale pore will be refined to change transport properties (L. Huang et al., 2023). The nanoscale confinement alters the water dynamics so it will somehow accelerate the dissolution but strongly suppress the kinetics of precipitation process during reactions (see Fig. 2c) (L. Huang et al., 2025b), finally determining the efficiency and capacity of CO_2 storage.

The knowledge to control optimal relative humidity (RH) is crucial for fast engineered CO_2 mineralization, as the kinetics of carbonation of cementitious materials are strongly governed by the water layer on surface and in pores. RH regulates the degree of water saturation within mesopores and surface water film, which in turn plays a pivotal role in determining CO_2 adsorption capacity. Notably, the most significant CO_2 uptake is observed at the onset of capillary condensation when mesopores begin to fill with metastable, density-fluctuating water (Li et al., 2024). As demonstrated in Fig. 2d, the optimum RH for CO_2 uptake increases as the pore size goes larger, which follows a Kelvin relationship for water vapor to liquid condensation transition. The surface hydrophilicity of minerals significantly influences the critical RH required for optimal CO_2 docking. Specifically, minerals with lower hydrophilicity tend to exhibit higher optimal carbonation RH. In the case of C–S–H, a reduction in the Ca/Si ratio enhances surface hydrophilicity, hence it lowers the RH threshold at which CO_2 uptake most effective (Li et al., 2025). Moreover, carbonation products such as calcium carbonates continuously alter the pore size distribution and therefore affect gas transport and reactivity (Morandeau et al., 2014). The relative high water content may also cause clogging effect on pore structure, so some work (Isgor and Razaqpur, 2004) proposed to a bilinear decay function to account for the influence of carbonation on both moisture and CO_2 transport. However, the dynamic structural change in response to the moisture content really depends on the water to binder ratio, which is yet to be clearly understood.

Further studies are required to establish adaptive control strategies for RH and CO_2 concentration in practical applications to match the dynamical change of microstructure and composition toward optimization of long-term CO_2 storage capacity. The enforced carbonation treatment under aqueous state shows promising efficiency advantage (Jiang et al., 2024), but the kinetic control for large-volume implementation lacks a thorough understanding especially for fluid dynamics at stirring, thermal effect from the large volume reaction and these effects on the end-phases. Alternative techniques to tailor the structure of cement-based materials and to address kinetic and diffusion limits are also emerging as an effective method (Yu et al., 2025) but further work is needed to realize the application.

2.2. *Performance concern after CO_2 uptake in cement*

As cement and concrete systems are explored to store CO_2 through mineralization, a primary barrier to widespread adoption remains in preservation or improvement of engineering performance, particularly mechanical performance and durability. The ability of cementitious materials to act as CO_2 sinks arises from carbonation reaction. However, this reaction changes the physical, chemical, and microstructural properties of the material, leading to complex trade-offs between carbon sequestration and long-term performance.

In general, carbonation of cement-based materials will densify the microstructure and increase the compressive strength of the matrix. As illustrated in Fig. 3a, the enhanced CO_2 uptake shows a positive effect on the strength supported by available data from previous studies (Chinzorigt et al., 2020; Liu et al., 2020, 2022, 2021; Mahoutian et al., 2015; Salman et al., 2015; Wang et al., 2019). However, the uptake of CO_2 in the fresh state raises concerns regarding both workability and mechanical performance. Liu et al. (2021) found that increasing CO_2 absorption amount could cause a large loss of fluidity in fresh cement paste, mainly due to the formation of calcium carbonate and the reduction in the free water content, which also showed a mild negative effect on early strength development, especially flexural strength. When

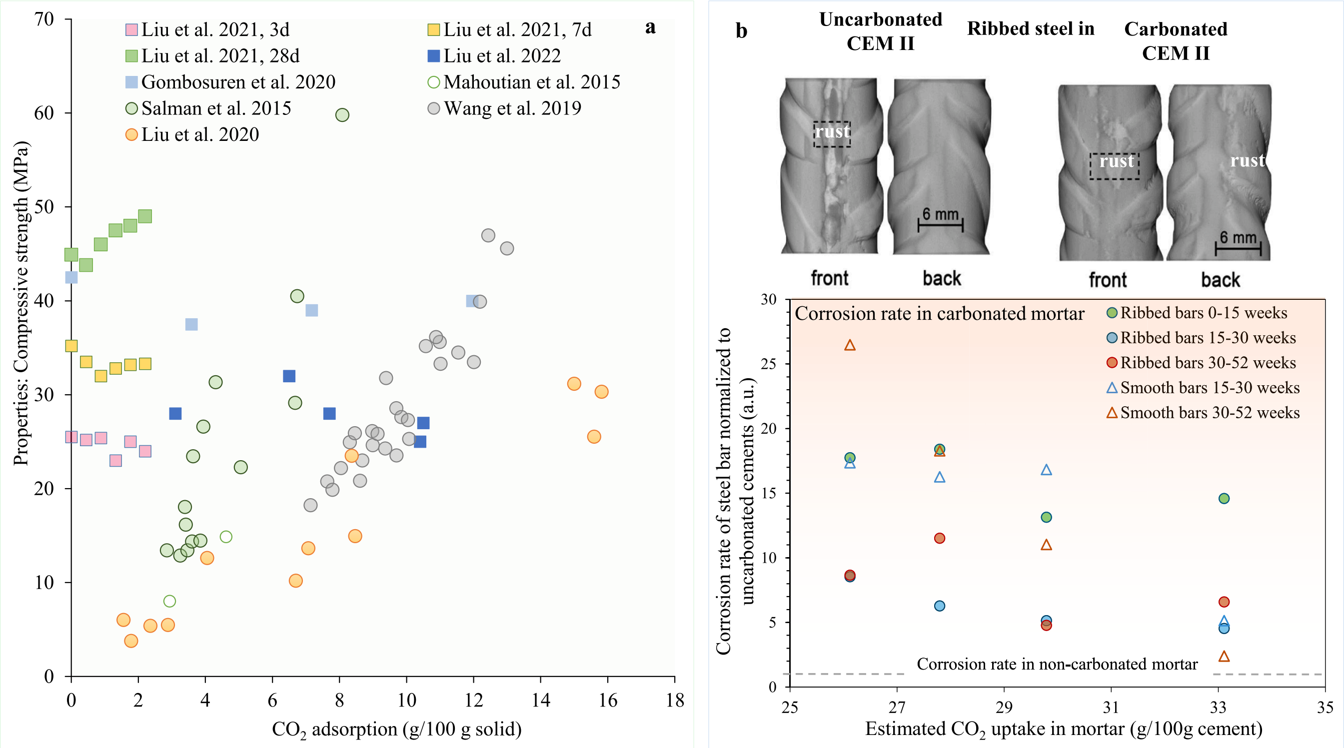

Fig. 3. Effects of CO_2 uptake on concrete mechanical performance and durability. (a) Influence on the compressive strength of Portland cement (square) and steel slag as the binder (circle) with data adopted from (Chinzorigt et al., 2020; Liu et al., 2020, 2022, 2021; Mahoutian et al., 2015; Salman et al., 2015; Wang et al., 2019), (b) Influence of CO_2 uptake on reinforcement corrosion rate under highly humid environment with data adopted from (Hren et al., 2021).

alkaline waste is valorized as cementitious by mineralization, the performance of concrete is highly dependent on the type and origin of the raw materials. For example, steel slag, a highly reactive carbonatable binder, responds favorably to CO_2 curing by achieving rapid hardening and significant strength gains, making it a promising alternative binder with CO_2 sequestration potential (Hu et al., 2024). However, the approaches reported in studies were mainly based on lab-scale experiments. It is challenging to implement at upscale due to the special curing requirement compared to traditional construction processes, so its current applications are very limited (Liu et al., 2023).

Another way is to use CO_2-cured recycled waste as aggregate or supplementary cementitious materials (SCMs) to replace natural stones and Portland cement, respectively (Mo et al., 2017). The uptake of CO_2 in recycled aggregates causes a reduction in porosity and a densification of the microstructure at the interfacial transition zones (Huang et al., 2019; Wu et al., 2022; Zhan et al., 2019). Therefore, the performance of concrete with carbonated recycled aggregates is normally better than that with noncarbonated aggregates, but the performance is still compromised when replacing natural aggregates with even carbonated recycled aggregates (Russo and Lollini, 2022). In addition, the use of carbonated recycled concrete powders (RCPs) markedly decreased the workability of fresh concrete. A 30 % dose of RCPs was reported to cause a maximum of ~50 % decrease in slump (Mehdizadeh et al., 2021). The use of RCPs substituting 38.25 % of cement clinker showed much better performance than those replaced with limestone, but its compressive strength at 28 days is only about 80 % of the designed strength of clinker (Ca. 52.5 MPa) (Zajac et al., 2020b). The CO_2 uptake in RCPs will transform the hydration products into different mineral phases such as polymorphs of calcium carbonates, silica gel, alumina gel, and gypsum, among which calcite mainly work as filler and the others can be reactive to work as SCMs (Poon et al., 2023). The portion of gels and carbonates decides the pozzolanic reactivity of RCPs for reliable mechanical performance.

Beyond strength, durability is critically important for the role of concrete as a CO_2 storage medium because the stability of stored CO_2 depends on the structural integrity and resistance of the material to degrade over time. Any deterioration could lead to the release of bound CO_2 or the loss of functional service life, affecting its environmental benefit. Therefore, durability concerns cannot be decoupled from lifecycle emissions evaluation, particularly for applications requiring long service life and exposure to aggressive environments. Although carbonation reduces total porosity and permeability, thus potentially lowering the ingress of deleterious agents, it also alters phase assemblage and pore solution chemistry, especially pH (Steffens et al., 2002). Furthermore, the consumption of portlandite and the decomposition of Friedel salts can reduce the capacity to bind chloride, as observed in both experimental studies (Chang, 2017) and simulation (L. Huang et al., 2025a). This reduction in binding capacity lowers the resistance of concrete to chloride ingress, which may accelerate reinforcement corrosion and overall deterioration.

The impact of carbonation is also influenced by the type of binder. SCM-rich systems, such as those containing slag or fly ash, show different pore structures and lower portlandite contents, often leading to accelerated carbonation rates and potentially more severe reductions in chloride-binding capacity (Papadakis, 2000). Hren et al. (2021) investigated a direct evaluation of the influence of carbonation on steel bars, which was evaluated by the galvanostatic pulse method. As shown in Fig. 3b, they found that the uptake of CO_2 by accelerated carbonation strongly increases the corrosion rate of steel in blended cements with SCMs; the increasing level stays in a range of 5 to 30 times based on the exposure time and cement types. As highlighted by Van et al. (2024) that while carbonation can account for up to 30 % of cement-derived CO_2 emissions over the lifecycle, if durability is not considered, the unstable uptake may limit its climate benefit. Therefore, comprehensive work is needed to address performance concerns regarding the application of CO_2-stored cement and concrete materials, especially for their durability.

2.3. Cost and efficiency of emerging carbon-storing binders

Besides the traditional Portland cement and alkali wastes, magnesium-rich materials are abundant in nature with a potential to produce cementitious materials while storing CO_2. Olivine materials have been extensively explored in geological carbon storage (Zhang et al., 2022) but its production for cementitious materials remains large unexplored due to their low carbonation reactivity. Instead, magnesia cement produced from magnesite is emerging as a promising alternative to Portland cement due to its high CO_2 store capacity (Bernard et al., 2023). As summarized in Fig. 4a, the CO_2 storage capacity in magnesia cement ranges from 0.75 to 1.1 g/g raw materials, depending on the hydration state of the raw materials (Morrison et al., 2016).

However, the challenges in scaling up magnesium cements for CO_2 storage include economic feasibility, resource availability, and the relatively low pH that may cause corrosion concerns for steel reinforcement. The global production of magnesite is around 22 million tonnes according to USGS data (Fig. 4b) (Hatfield, 2025), which is substantially less than the cement demand level of cement (~4 Gt). More sources of magnesium need to be explored, such as use of desalination brines or seawater directly (Shahmansouri et al., 2015). Due to the expensive nature of the magnesium source, most MgO-based cements have a much higher production cost than that of Portland cement (Walling and Provis, 2016). Even if magnesium is extracted from seawater or brines, the use of chemicals would further increase the cost of the production process and the cost can reach up to a thousand dollars per ton or even higher (Özkan et al., 2016; Shahmansouri et al., 2015). As shown in Fig. 4c, the production cost of magnesia cement is at least 2 and up to 10 times higher than that of PC.

The most mature way to produce magnesia is through the calcination of magnesite (X. Huang et al., 2025). However, concerns over energy intensity and emissions from this technique remain the same as those of PC production. Life cycle assessment (LCA) for the comparison of PC and magnesia production showed that although most of the environmental impacts of magnesia cement are lower than those of PC, its effects on climate change and land use are higher than that of PC (Fig. 4d) (Ruan and Unluer, 2016). A recent study reported the possibility of converting Mg-rich silicates to dicalcium silicates and magnesia through a thermal exchange reaction (Chen and Kanan, 2025), but the energy demand and especially the cost of such a process have not been adequately evaluated. Although the wet route $Mg(OH)_2$ production process showed the potential to valorize the rejected brine into a carbon storing cement (Singh et al., 2022; Ventimiglia et al., 2025), and electrochemical routes show promise because they rely primarily on low-cost renewable electricity for powering (Badjatya et al., 2022), rigorous techno-economic analysis is required to assess the scalability of these techniques to match the current cement market.

Belite-rich cements have gained renewed attention for their synergy with carbonation curing, offering both reduced CO_2 emissions (due to lower CaO content) and enhanced mechanical performance through the precipitation of stable carbonate phases. Carbonation hardening of belite clinker phases proceeds via dissolution–precipitation, where portlandite and C–S–H partially decalcify, leading to the formation of calcite, aragonite, or vaterite, which densify the microstructure and improve early strength (Jang and Lee, 2016). Other formulations, such as ternesite–belite blends, have demonstrated accelerated strength gain under CO_2 curing while maintaining long-term stability (Zhang et al., 2025). These systems also display reduced autogenous shrinkage and potentially lower lifecycle CO_2 footprints compared with alite-rich cements (Wang et al., 2025). Despite promising laboratory results, scaling challenges include the need for controlled CO_2 supply, curing chamber infrastructure, and optimization for varying ambient conditions, addressing these factors that will influence both cost and industrial adoption potential. The capital expenditure required for producing

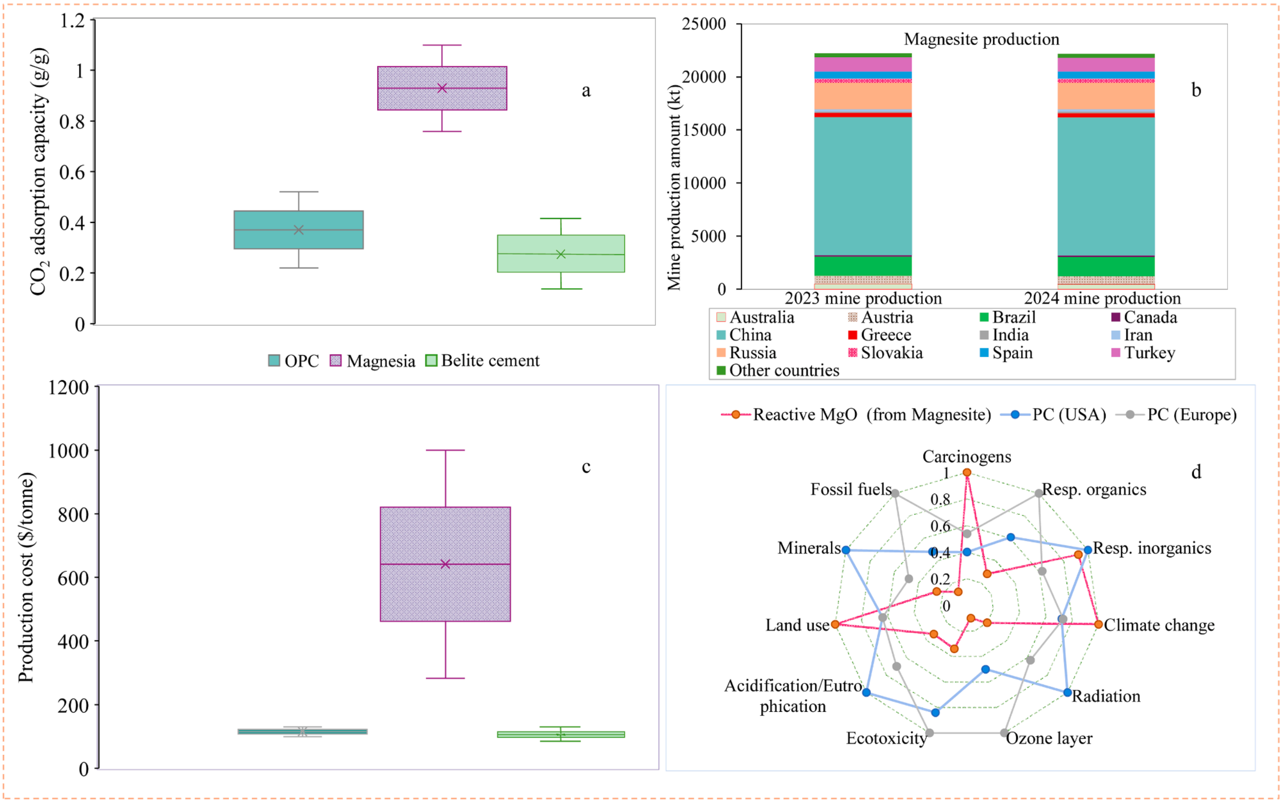

Fig. 4. A comparison of Portland cement (PC), belite and magnesia cement: CO$_2$ adsorption capacity (Li et al., 2021; Morrison et al., 2016; Wang et al., 2011) (a), the mining amount of raw materials like magnesite (Hatfield, 2025) (b), general production cost (McLellan et al., 2011; Nguyen et al., 2018; zkan et al., 2016; Shahmansouri et al., 2015) (c), and life cycle analysis of environmental influence for production (Ruan and Unluer, 2016) (d).

carbonatable belite cement is generally expected to align closely with that of ordinary Portland cement, as the raw materials is similar and it can be manufactured using conventional cement kilns and infrastructure (Gartner and Sui, 2018). Due to a lower CaO in belite cement, the CO$_2$ uptake capacity of them is a bit weaker than OPC with a range of approximately 0.15–0.4 g/g binder (Fig. 4a) depending on the water to binder ration of mix (Siddique et al., 2020). To the date of this writing work, there is no systematic LCA and economic analysis of belite cement production, however, its emissions would be lower than OPC due to the lower temperature requirement and the less use of limestone.

2.4. Effective LCA models

It is of great significance to accurately account for CO$_2$ uptake in various types of cement-based materials so that we can correctly determine their carbon storage capacity and evaluate their economic viability, particularly in the context of carbon taxation and monetization of environmental benefits for large-scale implementation. A comprehensive LCA of carbon storage concrete must consider CO$_2$ uptake in all component components, such as cement paste, aggregates, and recycled fines, and account for all hydration products with different uptake capacities (Steiner et al., 2020), throughout the material's whole service life. To ensure accurate predictions, this requires the integration of chemical corrosion models that simulate deterioration under various environmental exposures, along with a model for the carbonation kinetics of hydrated cement phases. Only with such detailed modeling and quantification can the true carbon offset potential of carbon-stored concrete systems be realized and optimized for climate-positive construction practices.

Most current estimations of storage capacity have overlooked or underestimated carbonation efficiency. Some overestimated the capacity by ideally assuming a full carbonation without considering carbonation kinetics, such as in the currently published work by Van et al. (2025). Xi et al. (2016) established a comprehensive analytical model describing carbonation chemistry with up-to-date data in 2013 to estimate regional and global CO$_2$ uptake in cement materials during their service life, demolition and recycling of concrete waste. At that time, it was a very comprehensive and novel consideration for this data, but current concrete mixes have evolved significantly with the use of SCMs and carbon storing binders cured via accelerated carbonation curing. Therefore, this model will apparently underestimate CO$_2$ uptake in emerging cement and concrete materials. Moreover, the previous models did not account for dynamic carbonation over decades, regional climate variations, or the evolvingcomposition of blended cement. Concrete with carbon-stored binders and aggregates still absorbs CO$_2$ during its service life (Gluth and Bernal, 2025). Since incorporating re-carbonation into such inventories necessitates estimating the carbonation potential, emerging methodologies are being developed to enable cradle-to-gate LCA of these products (Kumar et al., 2024). To assess the net impact of climate, next-generation LCA models must integrate CO$_2$ uptake over time, concrete durability, dynamic carbonation kinetics related to building typology, and evolving compositions during carbonation reaction.

The current analysis of the potential for CO$_2$ mineralization in cement has been focused primarily on global-scale storage capacities and the quantification of theoretical maximum values, without considering critical demand-side factors such as the market size of CO$_2$ mineralization products, their applications (i.e., the properties of the material after CO$_2$ adsorption) and the economic viability of these production processes. These factors are crucial because they can significantly constrain commercial feasibility, deployment scale, and overall decarbonization potential. In many cases, the CO$_2$ uptake potential of commercial CO$_2$ mineralization and utilization technologies has been overstated due to the inappropriate assessment framework

(Driver et al., 2024). Effective LCA models must move beyond the idealized assumption of complete carbonation by explicitly accounting for carbonation kinetics, transport processes, and chemical corrosion models, so that it yields more realistic predictions of CO_2 storage capacity and service-life performance. The actual CO_2 uptake capacity of in-service buildings is influenced by environmental conditions and climatic history. However, such data remain largely undocumented, and related investigations are currently being advanced within some technical committees in RILEM.

3. A scalable pathway for the future of concrete carbon storage

The Intergovernmental Panel on Climate Change (IPCC) has identified cement-based materials within the built environment as significant potential carbon sinks (IPCC, 2023). However, a large part of the storage potential remained unexplored, so the realistic CO_2 storage in concrete materials using an economically competitive technology was about 0.39 Gt CO_2-eq globally (Driver et al., 2024), which is <10 % of the potential in alkaline wastes without consideration of aggregates and fillers (Pan et al., 2020). Therefore, in this section, a bottom-up technological roadmap is proposed to unlock the potential carbon storage in cement and concrete materials at an economically scalable level, prioritizing fundamental techniques to create value-added mineralization and upscale carbon storage in buildings.

3.1. Affordable techniques for tailor-made carbonation products

As illustrated in Fig. 5, the first phase in realizing a carbon-storing concrete future lies in the development of affordable carbonation curing and CO_2 mineralization technologies capable of producing end-products with value-added properties. When these processes are optimized to produce cementitious materials with targeted performance characteristics, the value of carbonated calcium and magnesium rich feedstocks can be significantly enhanced, potentially making them economically competitive with conventional construction materials. However, achieving this goal is technically complex, as the thermodynamics and kinetics of CO_2 mineralization are governed by multiple interdependent variables, including impurity levels, temperature, pH, CO_2 pressure, and the aqueous chemistry of the system. These factors collectively influence the formation of carbonate polymorphs, which often result in a mixture of calcite, aragonite, and vaterite, rather than a targeted phase (La Plante et al., 2021; Romanov et al., 2015; Rostami et al., 2012).

The mineralogical outcome of the carbonation reaction is not merely a scientific knowledge interest; it critically determines the practical performance of the product in cement and concrete applications. For example, calcite only works as filler, and excessive use will significantly undermine concrete performance of the concrete (Hay et al., 2023), while aragonite or amorphous phases may offer higher reactivity that modifies the phase assemblage of the hydration products and the microstructure (Zhao et al., 2023). Controlling the selectivity and morphology of these mineral phases within complex impure matrices remains a formidable challenge, particularly when dealing with real-world industrial residues.

Current approaches for tailoring carbonates precipitation include chelation control, pH adjust, seed crystallization, and templating techniques to precisely engineer mineral nucleation, crystal size, and polymorph stability. Chelating agents, such as polyacrylic acid or EDTA, can accelerate the sequestering of calcium or magnesium ions and promote controlled carbonation pathways (Kulak et al., 2007; Niu et al., 2022). pH modulation strategies, either through acid/base additives or microbial metabolism to alter supersaturation dynamics, enable selective precipitation of metastable or thermodynamically preferred carbonates (Hoffmann et al., 2021). Seed crystallization, using preformed carbonate or hydroxide nanocrystals, offers a powerful means to accelerate hydration and carbonation kinetics, reduce induction periods and enhance phase purity (Meldrum, 2003). Finally, templating techniques, employing either organic macromolecules, biopolymers, or nanostructured inorganic frameworks, provide spatial and chemical guidance for crystal growth, often mimicking biomineralization pathways to achieve hierarchical morphologies (Gower, 2008a). However, these methods are neither technically nor economically viable to be adopted in the instrial scale production of cement materials.

Moreover, researchers have explored the use of chemical additives, such as amines and bio enzymes, to enhance CO_2 uptake and guide the precipitation pathway toward desirable carbonate morphologies(Sanna et al., 2014; Niu et al., 2022). These additives can significantly improve the dissolution kinetics Ca or Mg silicates and promote the nucleation of specific polymorphs. However, their efficiency is highly composition dependent. The chemical composition of the source material (e.g., the presence of Si, Fe, or Al), along with process parameters such as flow rate, mixing intensity, and reactor design, alters the interaction between additive and substrate. While additives may accelerate dissolution, they can also inhibit crystallization. For example, ligands adsorbed on

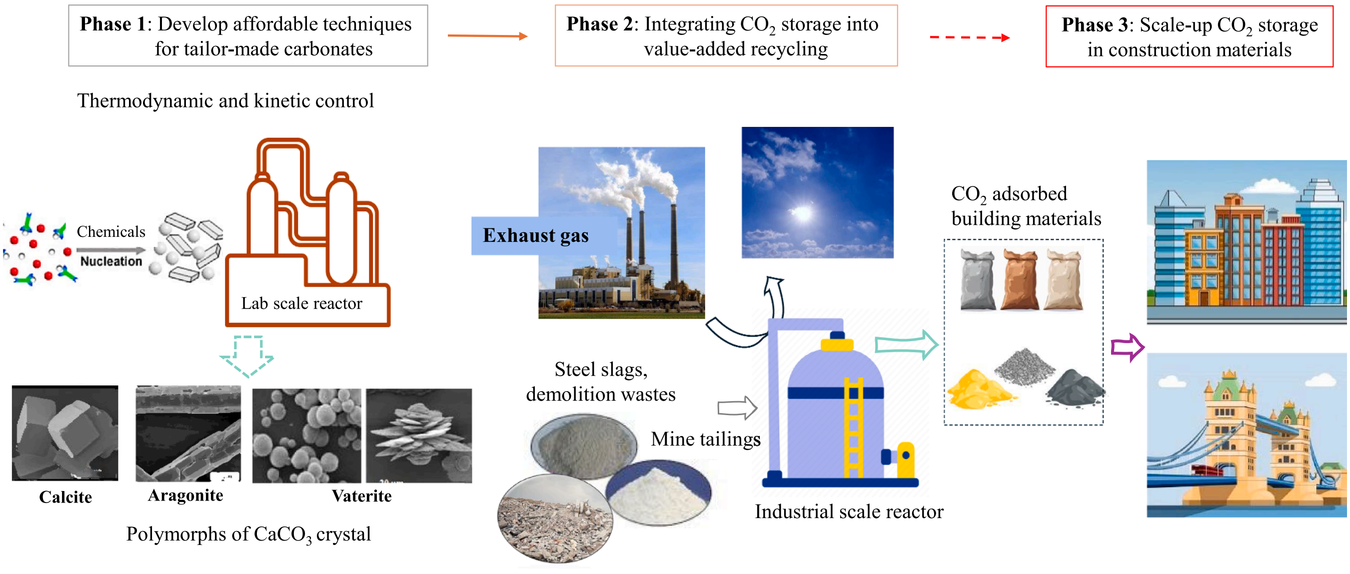

Fig. 5. Technological pathways to unlock value-added CO_2 storage in cement and concrete materials.

mineral surfaces, such as magnesite, can block active sites, suppressing the nucleation and growth of carbonate phases (Gautier et al., 2016).

Therefore, it is essential to develop affordable techniques that enable the fundamental control of carbonate formation and precipitation of reactive gels, such as silica or alumina-based hydrates, which contribute to the strength and durability of concrete. Fundamental work on establishing phase diagram among carbonates, gel and impure elements system will be very useful for tailor-made design. To navigate this highly multivariate design space, emerging tools from artificial intelligence, such as deep learning, offer efficiency boosting potential. When experimental data are integrated with predictive modelling, it becomes feasible to simulate and optimize carbonation reactions allowing for the targeted synthesis of polymorphs and gels tailored to specific performance goals. Besides the technological challenges, tailored carbonate formation strategies face cost–efficiency barriers in low-value cement markets. High additive costs, specialized templates, or engineered seeds often exceed the price tolerance for mass applications in residential building and infrastructure. Efficiency is also hindered by the need for precise pH, ion balance, and curing gas control, which are difficult to maintain outside precast settings. Field variability induces different carbonation, reducing performance and sequestration benefits. Future adoption will rely on how to bridge the gap between niche high-performance concretes and large scale, low-margin applications where the climate benefit could be very significant.

3.2. Integrating carbon storage with recycling alkaline waste

Building on the need for precision-controlled carbonation processes, the next strategic step involves integrating CO_2 mineralization with the recycling of alkaline industrial waste. While the natural carbonation of concrete in service contributes incrementally to CO_2 uptake, a much greater opportunity lies in the engineered carbonation of fine demolition waste and industrial residues. Among these, recycled concrete powders, along with alkaline by-products such as steel slag, mine tailings and coal fly ash, offer tremendous potential not only for CO_2 sequestration but also for valorization as alternative concrete materials in building systems. One key advantage of these technologies is their ability to integrate CO_2 mineralization into existing industrial processes, facilitating rapid industrial upgrading with relatively low barriers to adoption. In this context, incorporating the recycling of alkaline industrial wastes into carbon storage strategies represents a promising way to further improve process efficiency and sustainability while using current industrial infrastructures (Li and Unluer, 2025).

Globally, approximately two billion tonnes of alkaline residues are generated annually from heavy industries like steel and mining (Renforth, 2019). These wastes are commonly stored or dumped, which poses environmental risks due to their high alkalinity and the potential leaching of heavy metals into soil and water (Gomes et al., 2016). However, the same alkaline nature that makes these materials hazardous also gives them high reactivity to CO_2, allowing mineral carbonation that can sequester an estimated 4.02 Gt of CO_2 per year, which corresponds to 12.5 % of global anthropogenic CO_2 emissions (Pan et al., 2020). Beyond their CO_2 uptake potential, these residues often share chemical similarities with Portland cement, including high contents of Ca, Mg, Si, and Al. Once carbonated, they can produce carbonate phases and gels that exhibit promising properties for reuse as cement or concrete constituents (Bobicki et al., 2012; Galvez-Martos et al., 2016). This dual functionality of waste recycling and carbon storage represents a powerful pathway to both decarbonizing construction and creating value through circular resource flows.

However, to fully realize this opportunity, economical carbonation systems must be developed to enhance the mineralization efficiency and phase selectivity from these complex materials. Several key areas require focused attention:

- Low-energy processing methods should be prioritized, including strategies for pretreatment, particle size reduction, and selective metal ion extraction, all of which aim to increase reactivity and control the formation of desired end-products.
- A robust LCA and life cycle cost (LCC) analysis of engineered carbonation systems is essential to quantify their environmental and economic value, particularly compared to conventional waste disposal practices.
- The performance of carbonated waste-derived materials must be thoroughly characterized, from fresh state behavior (e.g., workability and setting time) to mechanical strength, durability, and long-term leaching risk of heavy metals.
- In addition, its performance after carbonation, including any changes due to additional exposure to CO_2 during service life, should be rigorously evaluated.

By integrating waste recycling with carbon mineralization, this path represents a grounded and scalable strategy to simultaneously mitigate industrial CO_2 emissions, reduce hazardous waste streams, and generate value-added, low-carbon construction materials. Given its potential to lower material costs and offset carbon liabilities, it may also prove economically feasible and attractive to industry, policymakers, and the scientific community.

3.3. Addressing durability concern

While adopting a new generation of carbon-stored building materials, the durability of the infrastructure should always be a critical factor to be counted for safety and sustainability. Carbonation has long been considered a threat to the durability of reinforced concrete due to the risk of steel depassivation (Hren et al., 2021). Whether stored CO_2 will significantly impact corrosion resistance depends in some way on the scenario considered. As demonstrated in Fig. 6a, the chloride migration coefficient as one of the most important properties determining steel bar corrosion under an aggressive exposure environment, its value was reduced by adsorption of CO_2 in recycled aggregates compared to untreated recycled aggregates (Blackshaw et al., 2024; Li et al., 2018; Liang et al., 2020). However, the coefficient for concrete with carbonated cement showed significant increases, which means a faster ingress of corrosive ions. As highlighted in Section 2.2, the corrosion rate of the steel bar would be greatly increased with a similar chloride level.

One of the solutions is to use carbon-stored concrete in unreinforced structures, but this kind of application is very limited, since most of concrete infostructures require reinforcement in its design. The corrosion chemistry of steel bars (without chloride) can be demonstrated by the Pourbaix diagram (Angst et al., 2020) shown in Fig. 6b Reinforcement in atmospheric structures typically maintains a thermodynamically stable passive state, even at relatively low pH levels around 8. However, the presence of chlorides, even at modest concentrations, poses a significant threat to this passivity. Chlorides are well known to destabilize the protective passive film, with the chloride-to-hydroxyl ion ratio (Cl^-/OH^-) recognized as a crucial factor in this process (Hausmann, 1967). A drop in pH markedly increases the Cl^-/OH^- ratio, so the carbonation induced a strong concern of reinforcement corrosion.

Previous work reveals that moisture availability on the steel surface, not carbonation alone, is the dominant driver of corrosion (exampled in Fig. 6c). Studies in diverse climates show that corrosion damage is often weak in carbonated structures unless persistent moisture reaches the rebar (Angst et al., 2019). Moisture is also one of the key factors controlling the mineralization kinetics and capacity of CO_2. Therefore, to address the durability concern of carbon-stored concrete, more work can be focused on developing frameworks for controlling moisture transport, accounting for cover depth, microstructure, and exposure conditions, developing models accounting for the complex interaction between water and microstructure (Huang et al., 2022) that accurately

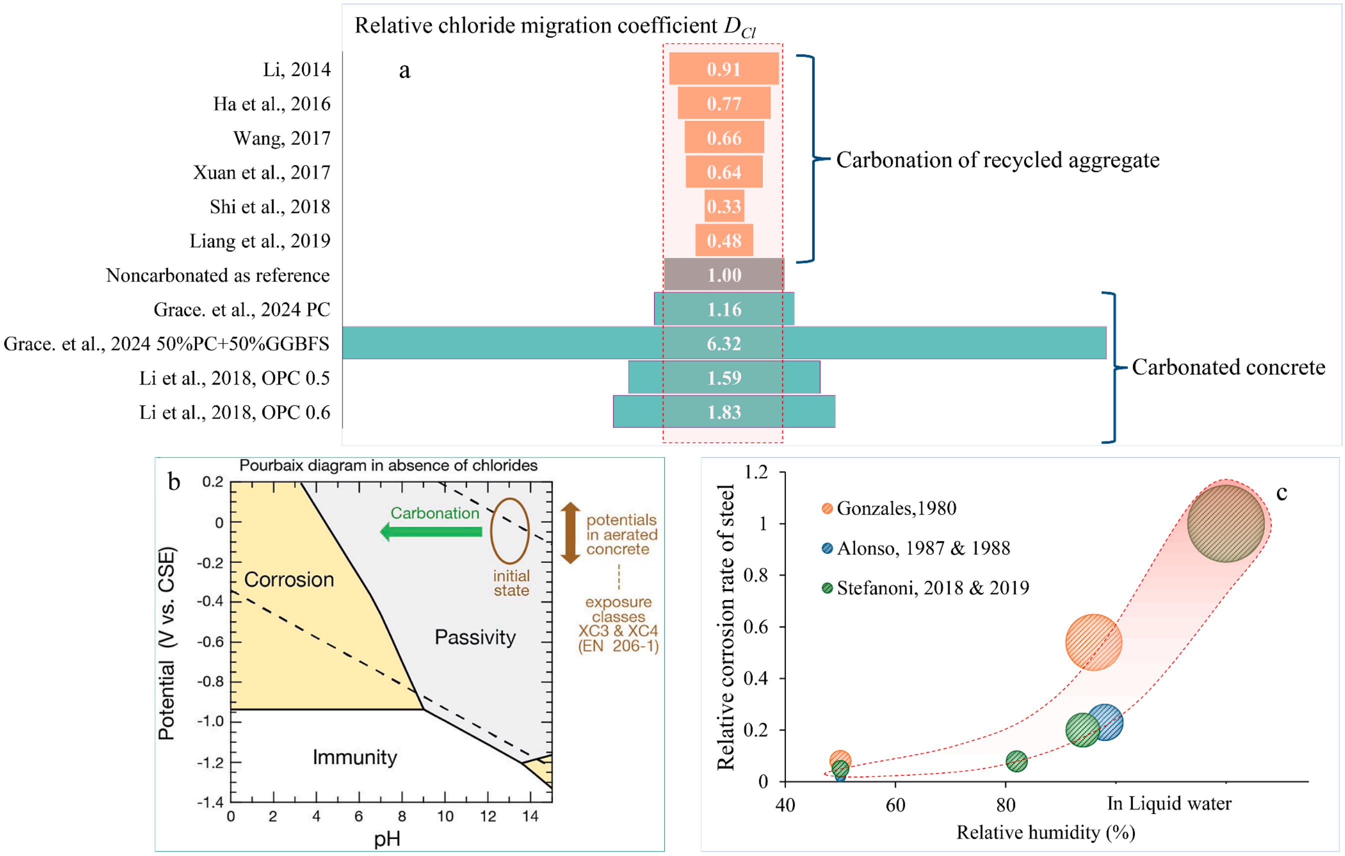

Fig. 6. Key factors in assessing the corrosion resistance of reinforced concrete with CO_2 stored. (a) Effect of CO_2 adsorption on the chloride migration coefficient of concrete having recycled aggregates, with data adopted from (Blackshaw et al., 2024; Li et al., 2018; Liang et al., 2020); (b) Pourbaix diagram for corrosion chemistry of steel bar after subjected to carbonation (Angst et al., 2020), and (c) effect of moisture state on reinforcement corrosion with data from (Alonso et al., 1988; Alonso and Andrade, 1987; Gonzalez et al., 1980; Stefanoni et al., 2018).

simulate moisture transport and retention in carbonated concrete. Further systematic work is required on exploring mitigation strategies such as optimizing carbonation conditions to limit excessive pH reduction, engineering SCM blends that balance reactivity with alkalinity retention, and adopting protective measures such as surface sealants, corrosion inhibitors, or hybrid reinforcement approaches to reduce the moisture at interface. Continued integration of durability modelling and long-term field exposure studies will be essential to establish reliable pathways for deploying carbon-storing concretes without sacrificing structural performance.

3.4. Scaling up adoption of carbon-storing building materials

The final and equally critical phase in the path to carbon storage concrete is the large-scale adoption and implementation of carbon-stored building materials in new construction (Fig. 5). This transition should begin with the validation of mineralization technologies on a pilot scale, as demonstrated in earlier studies (Reddy et al., 2010), to produce a range of carbon-storing products, including cementitious binders, aggregates, fillers, and hybrid composite systems.

Parallel to pilot validation, efforts must be focused on developing industrial-scale applications, where the direct use of flue gas offers a practical and cost-effective pathway to CO_2 supply (Ostovari et al., 2021). Using flue gas not only allows access to concentrated CO_2 streams, but also provides residual heat, which can be harnessed to improve reaction kinetics and reduce the overall energy demand of the carbonation process (Naraharisetti et al., 2019). CO_2 is commonly emitted by high-energy-demand industries, such as power plants, which are frequently situated at considerable distances from key markets. This geographical disconnect may require the location of facilities for producing carbonated materials at emission sources. Otherwise, transporting CO_2 to production and consumption centers would entail additional costs and pose challenges related to safety and risk management (Li et al., 2022). Further optimization of the process at scale will require investigating the relationship between feedstock particle size, grinding energy, and carbonation efficiency to minimize energy input while maximizing CO_2 uptake.

To better bridge the gap between laboratory-scale findings and industrial-scale implementation, a data-driven machine learning modelling approach, integrated with targeted experimental validation, could systematically address the complexity of controlling carbonation efficiency in heterogeneous alkali wastes. Laboratory experiments provide essential insights into reaction mechanisms and compositional variability; however, large-volume processes introduce additional kinetic control factors that remain insufficiently understood, including the influence on the final mineral phases and mix design of carbon stored concretes. By training machine learning models on detailed laboratory-scale kinetic and compositional datasets with iteratively refining through pilot-scale trials, it becomes possible to capture the interplay between material heterogeneity and scale-dependent physical phenomena. Such hybrid modelling–validation frameworks have demonstrated improved predictive accuracy and process stability in analogous mineral processing and CO_2 sequestration systems (He et al., 2023; Sharma and Liu, 2022), which offers a promising pathway towards reliable and efficient carbonation performance at the industrial scale.

Beyond technological considerations, regulatory frameworks and standardization will play a decisive role in enabling widespread market adoption. At present, building codes and material standards vary significantly between regions, and many do not yet recognize the unique performance characteristics or environmental value of carbon-storing concretes. The absence of harmonized standards can create barriers to approval, introduce inconsistencies in performance, and delay the integration of these materials into mainstream construction practices (Barbhuiya et al., 2025). To address this, it is essential to consider the following points:

- Develop and implement clear technical standards and certification criteria for carbon-storing cement and concrete products.
- Integrate durability and performance assessments into existing concrete codes, ensuring that these materials meet structural safety requirements and long-term reliability benchmarks.
- Encourage the creation of green building certification programs and provide financial support for innovation and demonstration projects, helping to derisk investment and build stakeholder confidence (Erten and Kılkış, 2022).

Successful scaling will depend on a coordinated approach that aligns technical efficiency, regulatory readiness, and economic viability. Achieving this will allow carbon storage concrete to transition from research and demonstration to practical deployment, so that it contributes to global sustainable construction goals.

4. Concluding remarks

Cement and concrete, once viewed primarily as emissions-intensive materials, can be reimagined as useful enablers of climate mitigation through mineral carbonation. As this perspective highlights, substantial progress has been made in understanding the mechanisms, materials, and process technologies that underpin carbon storage in cementitious systems. However, the path to widespread implementation requires overcoming key barriers: improving the control of carbonation reactions in complex materials, ensuring mechanical and durability performance, reducing production costs, and aligning with standards and regulatory frameworks.

Scalable transition requires coordinated efforts across scientific disciplines, industrial sectors, and policy domains. Researchers must refine carbonation kinetics, design adaptive material systems, and explore novel routes to integrate CO_2 capture with waste valorization. AI can play a significant role in optimizing carbonation efficiency of the controlled chemical process and the LCA assessment. Industry must validate these solutions in real-world applications, leveraging pilot-scale demonstrations and advancing life-cycle assessments. Policymakers and regulators must establish technical criteria, carbon accounting protocols, and incentive mechanisms that recognize and reward the environmental value of carbon storage concretes.

As urbanization accelerates, the incorporation of carbon sequestration within the built environment represents a rare opportunity to transform infrastructure from a carbon liability into a climate asset. By combining materials science, engineering innovation and policy foresight, the next generation of cement and concrete can play a central role in achieving net zero ambitions and fostering long-term environmental resilience.

CRediT authorship contribution statement

Liming Huang: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Baodong Li:** Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, Conceptualization. **Xinping Zhu:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ning Li:** Writing – review & editing, Writing – original draft, Resources, Investigation, Formal analysis, Conceptualization. **Xin Zhang:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

We declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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