Emirates International University EIU

Research Article

Emirates International University Journal Issued. (5).(2026)
(2026) .(5) مجلة الجامعة الإماراتية الدولية. العدد

Mineral Carbonation of Construction and Demolition Waste for Sustainable Construction A Review

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Abstract

Construction and demolition waste (CDW) represents one of the largest global waste streams, while the cement industry contributes approximately 8% of anthropogenic CO_2 emissions. Mineral carbonation of CDW offers a dual-purpose solution, whereby the precipitation of $CaCO_3$ densifies the aggregate microstructure while permanently sequestering CO_2. This review synthesises peer-reviewed publications, addressing CDW characterisation, carbonation chemistry, accelerated carbonation methods, aggregate property improvements, concrete performance, CO_2 uptake quantification, and environmental assessment. Key findings indicate that accelerated carbonation can reduce recycled concrete aggregate water absorption by up to ~35% under optimised pressurised treatment, increase density by 1.5–5.0%, and improve 28-day compressive strength of recycled aggregate concrete by 7–33%, while sequestering approximately 27 to over 490 kg CO_2 per tonne of cement paste depending on CDW fraction, source quality, and treatment conditions. Carbonated recycled aggregate concrete achieves 27% lower global warming potential than natural-aggregate concrete in strength-standardised comparison. However, the alkalinity-durability trade-off, improved transport resistance alongside reduced pore-solution pH from ~12.5 to below 9, remains the most significant unresolved concern for reinforced applications. Critical research gaps include heterogeneous real-world CDW streams, long-term durability, industrial-scale process data, and harmonised measurement protocols. RILEM TC 309-MCP provides a foundational framework, and a phased research roadmap spanning short-, medium-, and long-term horizons is proposed to guide deployment.

Keywords

Construction and demolition waste; Accelerated carbonation; Recycled concrete aggregates; CO_2 sequestration; Alkalinity-durability trade-off.

Received	01/01/2026
Accepted	01/01/2026
Published	31/07/2026
Publisher	Emirates International University

ISSN	3104-6142
ISSN (Online)	3104-6150
DOI	10.64059/eiu.v3i1.98
Wikidata	Q137945151
ROR	03j6pc929

Citation:

Alameri, I. (2026). Mineral Carbonation of Construction and Demolition Waste for Sustainable Construction: A Review. Emirates International University Journal, 3(1), 24. https://doi.org/10.64059/eiu.v3i1.98

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Code:

9773104615005

الكربنة المعدنية لنفايات البناء والهدم لتحقيق التشييد المستدام: مراجعة

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الملخص

تمثل نفايات البناء والهدم (CDW) أحد أكبر تدفقات النفايات العالمية، بينما تساهم صناعة الأسمنت بنحو 8% من انبعاثات ثاني أكسيد الكربون .(CO_2) وتقدم الكربنة المعدنية لهذه النفايات حلاً مزدوجاً، حيث يؤدي ترسب كربونات الكالسيوم ($CaCO_3$)لتكثيف البنية المجهرية للركام مع احتجاز (CO_2) بصفة دائمة.

تستخلص هذه المراجعة الأبحاث المحكمة متناولةً توصيف النفايات، وكيمياء وطرق الكربنة المتسارعة، وتحسين خصائص الركام، وأداء الخرسانة، والتقييم البيئي. تشير النتائج إلى أن الكربنة المتسارعة تقلل امتصاص الماء للركام المعاد تدويره بنسبة تصل إلى 35% بالمعالجة المضغوطة، وتزيد كثافته بنسبة 1.5-5.0%، وتحسن مقاومة الانضغاط بعمر 28 يوماً بنسبة 7-33%. كما يتم احتجاز 27 إلى أكثر من 490 كجم من (CO_2) لكل طن من عجينة الأسمنت، اعتماداً على نسبة النفايات، وجودة المصدر، وظروف المعالجة.

تحقق خرسانة الركام المعاد تدويره المُكربنة احتمالية احترار عالمي (GWP) أقل بنسبة 27% مقارنة بالخرسانة الطبيعية. ومع ذلك، تظل المقايضة بين القلوية والديمومة — والمتمثلة في تحسن مقاومة النفاذية مع انخفاض الرقم الهيدروجيني (pH) للمحلول المسامي إلى أقل من 9 — الشاغل الأبرز لتطبيقات الخرسانة المسلحة.

تشمل الفجوات البحثية الحرجة عدم تجانس تدفقات النفايات في الواقع العملي، والديمومة طويلة المدى، وبيانات النطاق الصناعي، وبروتوكولات القياس الموحدة. وتوفر اللجنة الفنية (RILEM TC 309-MCP) إطاراً تأسيسياً، مع اقتراح خارطة طريق بحثية مرحلية تمتد لآفاق زمنية قصيرة، ومتوسطة، وطويلة المدى لتوجيه عملية التنفيذ والاعتماد.

الكلمات المفتاحية

نفايات البناء والهدم؛ الكربنة المُعجَّلة؛ الركام الخرساني المعاد تدويره؛ احتجاز ثاني أكسيد الكربون؛ الموازنة بين القلوية والمتانة.

1. Introduction

Construction and demolition waste (CDW) represents one of the largest waste streams globally, with the European Union construction sector alone accounting for approximately 38.4% of total EU waste generation in 2022 (Eurostat, 2024). Annual CDW generation in the EU ranges between 370 and 850 million tonnes, the wide spread reflecting whether excavated soils and dredging spoils fall inside the accounting boundary (Villoria Sáez & Osmani, 2019). The mineral fraction (concrete, masonry, tiles and ceramics) accounts for approximately 74.5% of demolition waste by mass(Alameri & Oltulu, 2020a, 2020b; Alameri & Oltulu, 2023; Alamerİ et al., 2020) .(Soultanidis & Voudrias, 2023), establishing it as the dominant material stream relevant to any valorisation strategy. China, the world's largest CDW producer, generates approximately 1,857 million tonnes annually, with projections exceeding 2,000 million tonnes by 2026 (Ding & Xiao, 2014) , while global estimates range from roughly 3.6 billion tonnes (Patil et al., 2024) to over 30 billion tonnes annually depending on system boundary (D. Peiris et al., 2025) . Compounding this waste burden is construction's outsized contribution to climate change, with the sector consuming 32% of global final energy and generating 34% of global CO_2 emissions in 2023, the cement industry in isolation contributing approximately 8% of global anthropogenic CO_2 emissions (International Energy, 2023; United Nations Environment et al., 2025) . Waste generation and carbon emissions are therefore not independent problems but two faces of the same material system, motivating solutions that address circularity and climate mitigation together.

Mineral carbonation of CDW is one such dual-purpose solution. A substantial fraction of CDW (recycled concrete aggregate (RCA), recycled masonry aggregate (RMA), and mixed recycled aggregate (MRA)) retains residual calcium-bearing cementitious phases that remain reactive toward carbon dioxide (CO_2) (Infante Gomes et al., 2021) . Under controlled exposure to elevated CO_2 concentrations, these phases dissolve and reprecipitate as thermodynamically stable calcium carbonate ($CaCO_3$) alongside an amorphous silica gel (Poon et al., 2023) . The resulting precipitates densify the aggregate microstructure by filling capillary pores and healing micro-cracks, improving physical and mechanical performance while locking CO_2 into a permanent mineral form (Zhan et al., 2020) . This dual benefit has driven rapid research growth over the past decade. This trend is independently confirmed by a recent bibliometric analysis. The analysis shows accelerating publication output in mineral carbonation of civil engineering materials since 2016 (Song et al., 2025) . Theoretical estimates further suggest that building materials could store more than 16 billion tonnes of CO_2 annually (Van Roijen et al., 2025) .

This growing literature has already been synthesised in several influential reviews, each with a distinct emphasis. (Poon et al., 2023) proposed a "total recycling" paradigm, arguing that essentially all concrete-derived waste fractions can be valorised through accelerated carbonation. (Shuvo et al., 2024) benchmarked four accelerated carbonation methods against one another for RCA treatment. According to (Villagran-Zaccardi et al., 2024) and (Snellings & Matschei, 2025) , writing under RILEM Technical Committee 309-MCP, respectively mapped the techno-economic bottlenecks facing carbonated RCA and proposed standardised terminology for the field.(Zhang et al., 2023) examined how carbonated fines and aggregates affect hydration, microstructure, and mechanical performance in new concrete, while (Zhang et al., 2024) focused specifically on long-term durability of concrete containing carbonated recycled aggregates. Despite this body of review literature, no single synthesis yet integrates the full spectrum of CDW mineral fractions (coarse and fine RCA, RMA, MRA, and recycled concrete fines/powders) within one framework combining quantitative meta-analysis, critical appraisal of evidence quality, and a prioritised research roadmap. Existing reviews focus heavily on RCA; coverage of RMA and MRA, which constitute a substantial share of real-world mixed CDW streams, remains sparse (Piccinali et al., 2022) ; (Suescum-Morales et al., 2021) Nor has the alkalinity-durability trade-off (the tension between the transport-property benefits of carbonation and the loss of pH buffering capacity protecting embedded steel from corrosion) been treated as a unifying theme (Xuan et al., 2017). This review addresses both gaps directly.

1.1 Review Methodology and Search Strategy

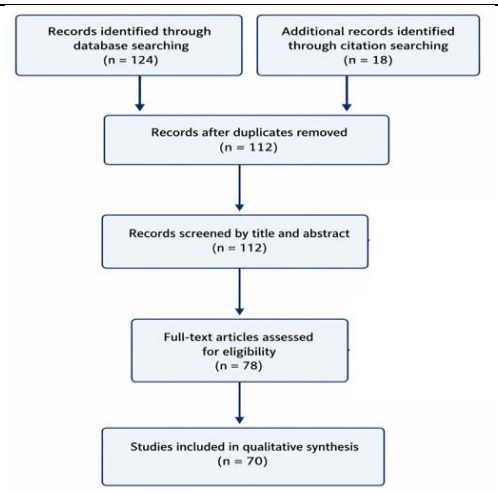

Figure 1: PRISMA 2020 flow diagram

This review follows the(Page et al., 2021) reporting guidelines for systematic reviews(Page et al., 2021). Peer-reviewed studies published in Scopus- and Web of Science-indexed journals were identified through structured database searching. Records were screened first by title and abstract, then by full-text assessment against inclusion criteria requiring quantitative data on CDW carbonation chemistry, treatment methods, property changes, or CO_2 uptake. The resulting evidence base comprises 70 studies retained for qualitative synthesis (Figure 1).

2. Characterisation of CDW as a Carbonation Precursor

2.1 Global Generation and Composition of CDW

Construction and demolition waste (CDW) is the largest single waste stream in the European Union by mass. In 2022, construction activities contributed 38.4% of total EU waste generation, making it the dominant waste-producing sector across member states (Eurostat, 2024) . Reported annual CDW generation in the EU ranges between 370 and 850 million tonnes, with the wide spread reflecting whether excavated soils and dredging spoils fall within the accounting boundary(Villoria Sáez & Osmani, 2019). The mineral fraction (concrete, masonry, tiles and ceramics) accounts for approximately 74.5% of demolition waste by mass (Soultanidis & Voudrias, 2023) , establishing it as the dominant material stream relevant to carbonation.

At the global scale, the figures are even more substantial. China, the world's largest CDW producer, generates approximately 1,857 million tonnes annually, with projections exceeding 2,000 million tonnes by 2026 (Ding & Xiao, 2014). The composition of CDW is inherently heterogeneous, varying by region, building stock age, and demolition practice. Typical CDW comprises concrete and masonry debris (60–90% of total mass across most EU member states), tiles and ceramics, glass, metals, plastics, wood, and bituminous materials (Dulshi Peiris et al., 2025; Villoria Sáez & Osmani, 2019). The concrete fraction is particularly dominant in regions with extensive reinforced-concrete construction from the post-war urbanisation boom (1950–1990) across Europe, North America, and Asia (Leemann et al., 2023) Recovery rates also require careful interpretation. The EU reports a headline recovery rate of approximately 89%. However, a substantial share of this reflects low-grade backfilling, not high-value material recycling (Caro et al., 2024) . This distinction matters for carbonation. Backfilled material does not realise the same CO_2 sequestration or aggregate-quality benefits as material processed for structural use.

2.2 Classification of CDW Mineral Fractions

Recycled aggregates derived from CDW are classified under EN 933-11:2009 into three principal categories based on composition and origin (Infante Gomes et al., 2021):

Recycled Concrete Aggregate (RCA): sourced from demolished concrete structures, characterised by natural aggregate particles coated with adhering old mortar and an "old" interfacial transition zone (ITZ) between the mortar and the original aggregate core. RCA is the most extensively studied CDW fraction for carbonation treatment(Infante Gomes et al., 2021; D. Peiris et al., 2025).

Recycled Masonry Aggregate (RMA): derived from brick, tile, and mortar demolition waste. RMA has lower CaO content than RCA but higher specific surface area, variable clay content, and greater porosity (Suescum-Morales et al., 2021). Despite forming a substantial share of real-world mixed CDW streams, RMA has received markedly less research attention than RCA (Dulshi Peiris et al., 2025).

Mixed Recycled Aggregate (MRA): variable proportions of concrete, mortar, unbound natural aggregate, and ceramic debris, typical of non-selective demolition (Saiz Martinez et al., 2023) . MRA is the most heterogeneous CDW fraction and the least represented in the carbonation literature relative to its real-world abundance (Liu et al., 2025) .

Fine fractions of each type (recycled fine aggregate <4 mm and recycled concrete fines <0.1–0.5 mm) have a higher specific surface area. This gives faster carbonation kinetics and greater CO_2 uptake per unit mass. But they also have greater compositional complexity from clay and gypsum contamination in RMA and MRA streams (Gurdjos & Bourgeois, 2025) .

2.3 Recycled Concrete Aggregates (RCA)

RCA is defined by its attached residual mortar, which constitutes 20–45% of mass in coarse fractions and 40–80% in fine fractions. This attached mortar governs both RCA's inferior physical performance relative to natural aggregate and its CO_2 uptake capacity, since the mortar carries essentially all of the reactive calcium-bearing phases (Zhang et al., 2023).

The scale of the quality deficit is substantial. Reported RCA dry density ranges around 2210 kg/m³, water absorption around 6.7%, fines content around 5.2%, and friability coefficient around 24.6% (Saiz Martinez et al., 2023), against natural-aggregate benchmarks of 2600–2750 kg/m³ density and 0.5–1.5% water absorption (Etxeberria & Castillo, 2023) . The variability in these figures is not merely a measurement artefact but reflects the inherent heterogeneity of attached-mortar content, which varies even within a narrow particle-size fraction of a single demolition batch (Leemann et al., 2023) . At 39.9% mortar content, RCA can exhibit specific gravity of 2.59 and water absorption of 3.8% (Muhammad et al., 2024) These values sit substantially above the absorption figures for higher-mortar-content RCA. This illustrates why specifying RCA with confidence remains a practical obstacle (Muhammad et al., 2024). The porous, weak, high-absorption mortar coating reduces resistance to crushing, impact, and abrasion relative to natural-aggregate concrete (Etxeberria & Castillo, 2023).

2.4 Recycled Masonry Aggregates (RMA)

RMA differs from natural aggregate in several key respects. These include higher porosity, higher water absorption, higher fines content (<0.075 mm), lower density, and inferior mechanical and freeze-thaw performance (Suescum-Morales et al., 2021). Reported apparent densities for RMA range from 1920 to 2340 kg/m³. Water absorption ranges from 3.7% up to 17.6%. That is roughly four times the absorption of typical RCA(D. Peiris et al., 2025)

The lower baseline quality of RMA reflects the higher porosity of the parent masonry units and weaker particle-paste bonding. However, this same porosity gives RMA a high specific surface area that may favour carbonation by improving CO_2 access (Suescum-Morales et al., 2021). Studies on porous mortars incorporating RMA fines confirm that RMA's fine fraction carbonates readily under both natural and accelerated (5% CO_2) curing, sequestering meaningful CO_2 even in non-optimised mixes (Merino-Lechuga et al., 2025) . Across both RCA and RMA, high attached-mortar porosity is the common root cause of elevated water absorption, reduced density, and restricted structural application (Dulshi Peiris et al., 2025).

2.5 Mixed Recycled Aggregates (MRA)

MRA is the most heterogeneous CDW fraction, combining variable proportions of concrete, mortar, unbound natural aggregate, and ceramic debris from non-selective demolition (Saiz Martinez et al., 2023) . Because its composition is essentially unpredictable batch-to-batch, MRA is the fraction for which standardised pre-treatment and quality control matter most (Liu et al., 2025) . Yet it is also the fraction least represented in the carbonation literature relative to its real-world abundance (Liu et al., 2025).

The heterogeneity of MRA has direct consequences for carbonation. Because batches vary, they differ in CaO content and reactive-phase distribution. Consequently, CO_2 uptake capacities also vary. The magnitude of property improvement differs too, even under the same treatment conditions (Saiz Martinez et al., 2023).

2.6 Fine Fractions: Recycled Concrete Fines (RCF) and CDW Fines

Fine CDW fractions (<4 mm), recycled concrete fines (RCF) and mixed CDW fines, are attractive carbonation feedstocks. They concentrate a disproportionate share of residual cement paste. They also offer the highest specific surface area of any CDW stream. Nevertheless, these materials are frequently dismissed as low-value "waste sand". This dismissal partly arises from wide batch-to-batch variations in particle shape and specific surface area. Such variability complicates quality control (Gurdjos & Bourgeois, 2025).

The mechanistic picture for RCF carbonation is the most detailed available for any CDW fraction. Portlandite, ettringite, and unhydrated clinker in RCF carbonate within one day. They form $CaCO_3$ and an alumina gel. Concurrently, decalcification of C-S-H produces silica gel and nanoscale $CaCO_3$. Under test conditions, theoretical carbonation potential reaches 14.0 g CO_2/100 g RCF. Wet carbonation achieves 8.48 g/100 g (60.6% of theoretical) after 120 minutes. Industrial-scale wet carbonation reaches an efficiency of 0.81. This equates to roughly 95 kg CO_2 per tonne of RCF (Gholizadeh-Vayghan & Snellings, 2022).

The high specific surface area of fine fractions gives them faster carbonation kinetics and higher per-unit-mass uptake than coarse fractions, but also makes them more sensitive to moisture content and more prone to agglomeration during processing (Gurdjos & Bourgeois, 2025) . This combination of high potential and high process sensitivity means that fine fractions require careful moisture control during carbonation to realise their theoretical advantage.

2.7 Chemical Composition of CDW Fractions

Carbonation potential depends fundamentally on chemical composition. CaO content is the single most useful proxy for it across fractions. RCA surfaces carry active hydration products. These are principally C-S-H and $Ca(OH)_2$. They initiate carbonation upon CO_2 exposure (Nedunuri et al., 2021). XRF characterisation shows that RCA has lower CaO and Al_2O_3 than natural aggregate. However, its loss-on-ignition is higher. This higher LOI reflects the carbonate and bound-water content of the attached mortar (Saiz Martinez et al., 2023) .

Table 1 summarises typical chemical compositions for RCA, RMA, MRA, RCF, and CDW fines. The data are compiled from (Nedunuri et al., 2021) and (Saiz Martinez et al., 2023) . CaO is highest in RCF (24–42%) and lowest in RMA (8–18%). SiO_2 dominates all fractions, with ranges spanning 30–65%. RMA exhibits the highest silica content. Al_2O_3 is elevated in RMA (8–15%) compared to RCA and RCF (3–8%). SO_3 levels are consistent across all materials (1–5%), reflecting gypsum contamination. LOI is notably high for RCF (10–25%) and CDW fines (10–20%), indicating substantial hydration products and carbonates.

Table 1 :Typical Chemical Composition of CDW Fractions (wt.%)

Oxide	RCA	RMA	MRA	RCF	CDW Fines
CaO	12–25	8–18	10–20	24–42	20–35
SiO_2	40–60	45–65	42–58	30–45	35–50
Al_2O_3	3–8	8–15	4–10	4–8	5–10
Fe_2O_3	2–5	3–6	2–5	2–4	2–5
MgO	1–3	1–4	1–3	1–3	1–3

Oxide	RCA	RMA	MRA	RCF	CDW Fines
SO_3	1–4	1–5	1–4	1–4	1–4
LOI	5–15	8–20	6–15	10–25	10–20

The CaO content of RCF (24–42%) is substantially higher than that of coarse RCA (12–25%). This difference reflects the concentration of cement paste in the fine fraction. This compositional disparity is the primary reason fine fractions have greater carbonation potential per unit mass than coarse fractions (Nedunuri et al., 2021) .

The SO_3 content across all fractions ranges from 1% to 5%. This sulfur originates from gypsum contamination. Common sources include plasterboard and other sulfate-bearing materials in CDW streams. This factor can affect carbonation chemistry. It must therefore be monitored for effective quality control (Saiz Martinez et al., 2023) .

2.8 Factors Governing Carbonation Reactivity

Carbonation reactivity emerges from the interplay of material properties and process parameters (Ali et al., 2026) . Intrinsic factors include cement paste content, mineralogy, and prior carbonation history. These establish the theoretical ceiling for CO_2 uptake. Extrinsic conditions include particle size, moisture, temperature, CO_2 concentration, pressure, and treatment method. These determine how much of that potential is realised in practice.

Table 2 summarises the optimal ranges and mechanistic roles for each controlling factor. Notable trade-offs exist across variables. Moisture must balance CO_2 dissolution against gas diffusion. Temperature accelerates early kinetics but risks C-S-H dehydration above 100°C (Sereng et al., 2021) . Pressure and concentration show diminishing returns beyond moderate thresholds (Mehmood et al., 2025). The choice of treatment method ultimately depends on whether rapid throughput, maximum uptake, or practical scalability is prioritised (Ali et al., 2026); (Shuvo et al., 2024) .

Table 2 :Factors Governing Carbonation Reactivity of CDW Fractions

Factor	Optimal Range	Mechanism of Influence	References
Cement paste content	Higher = greater uptake	Provides reactive Ca-bearing phases	(Zhang et al., 2023)
Particle size	Smaller = higher reactivity	Larger surface area for CO_2 diffusion	(Mehmood et al., 2025)
Relative humidity	50–55%	Balances CO_2 dissolution and diffusion	(Mehmood et al., 2025); (Sousanabadi Farahani et al., 2025)
Temperature	20–30°C	Accelerates kinetics; >100°C risks C-S-H dehydration	(Sereng et al., 2021)
CO_2 concentration	20–60%	Increases driving force for carbonation	(Mehmood et al., 2025); (Ali et al., 2026)
CO_2 pressure	40–60 psi (0.28–0.41 MPa)	Enhances penetration; overcomes diffusion barrier	(Sousanabadi Farahani et al., 2025) ; (Ding et al., 2023)
Mineralogy	High CaO content	Presence of reactive phases	(Nedunuri et al., 2021) ; (Sun et al., 2025)

2.9 Carbonation-Induced Modifications to Aggregate Properties

Carbonation systematically improves the physical, mechanical, and microstructural properties of CDW aggregates through $CaCO_3$/silica-gel precipitation and ITZ densification, with the improvements underpinned by

genuine strengthening of the atomic-scale bonding at the old-new interface rather than merely bulk pore-filling (Leemann et al., 2023; Lei et al., 2025; Tang et al., 2025).

The magnitude of improvement depends on the same governing factors. These include higher cement paste content, smaller particle size, optimal moisture, and elevated CO_2 concentration/pressure. Each factor yields larger property gains (Ding et al., 2023; Mehmood et al., 2025). However, these improvements are conditional. They require a well-characterised, single-fraction, laboratory-prepared precursor. They also require tightly controlled conditions.

3. Carbonation Chemistry and Mechanisms

3.1 Thermodynamics of Mineral Carbonation

Mineral carbonation of CDW is thermodynamically favourable. Calcium-bearing cement phases react with CO_2 to form stable $CaCO_3$. These reactions are exergonic under ambient conditions. The thermodynamic driving force is more than sufficient. It overcomes the associated kinetic barriers. Thermodynamic modelling of Portland cement phase assemblages confirms spontaneous carbonation. This occurs across the principal clinker phases and hydration products. Calcite is the thermodynamically favoured carbonate product under most exposure conditions. The pH falls continuously as portlandite and C-S-H are consumed (Reddy et al., 2022).

Mechanistically, the reaction proceeds via CO_2 dissolution, calcium leaching, and carbonate precipitation. CO_2 dissolves in the pore solution to form carbonic acid, which dissociates into HCO_3^- and CO_3^{2-}. This triggers the dissolution of calcium-bearing phases, releasing Ca^{2+}. $CaCO_3$ precipitates once the ion activity product exceeds its solubility product. Early in the process, CO_2 dissolution and transport are rate-limiting. As carbonation products accumulate, they armour reactive surfaces. At that point, precipitation kinetics take over as the controlling step. The theoretical maximum uptake for an ordinary Portland cement paste (w/c = 0.5, 28-day cure) is approximately 0.49 g CO_2/g cement. In practice, however, diffusion limits and pre-existing service-life carbonation cause realised uptake to fall substantially below this (Poon et al., 2023).

3.2 Portlandite Carbonation

Portlandite ($Ca(OH)_2$) carbonates most readily of the major cement phases. Its high solubility and rapid dissolution kinetics drive this reactivity, as shown in (Eq. 1):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad \textbf{(1)}$$

The theoretical CO_2 uptake capacity of portlandite reaches up to 59 mass%. Carbonation drives pore-solution pH downward. It falls from roughly 12.5–13.5 in uncarbonated paste to below 9 once fully carbonated. This shift has direct consequences for reinforcement corrosion risk. It removes the passivating alkalinity that protects embedded steel.

Portlandite also plays a protective secondary role. It consumes CO_2 preferentially. This limits C-S-H decalcification. It also prevents the shrinkage and cracking that decalcification would otherwise cause(Kangni-Foli et al., 2021).

3.3 C-S-H Decalcification

C-S-H, the most abundant hydration product in Portland cement paste, carbonates via progressive decalcification rather than complete conversion (Eq. 2):

$$\text{C-S-H} + CO_2 \rightarrow CaCO_3 + SiO_2 \cdot nH_2O \quad \textbf{(2)}$$

The Ca/Si ratio falls from approximately 1.7–2.0 in uncarbonated paste toward substantially lower values as decalcification proceeds, accompanied by silicate-chain polymerisation and the formation of an amorphous silica gel that co-precipitates with $CaCO_3$. This decalcification–polymerisation sequence is the principal driver of carbonation shrinkage and associated micro-cracking (Kangni-Foli et al., 2021) .

The use of model pastes has enabled evaluation of solid-volume changes from C-S-H carbonation. C-S-H decalcification and subsequent silica chain polymerisation were found responsible for carbonation shrinkage. This shrinkage can potentially lead to cracking. The results also highlight a protective role for portlandite. It limits C-S-H decalcification. It thereby reduces carbonation shrinkage and cracking.

3.4 Clinker Phase Carbonation

Unhydrated clinker relics (C_3S and C_2S) retain carbonation reactivity even decades after casting (Sun et al., 2025) . Equations (3) and (4) describe their carbonation reactions.

$$3CaO{\cdot}SiO_2 + 3CO_2 + nH_2O \rightarrow 3CaCO_3 + SiO_2{\cdot}nH_2O \quad \textbf{(3)}$$

$$2CaO{\cdot}SiO_2 + 2CO_2 + nH_2O \rightarrow 2CaCO_3 + SiO_2{\cdot}nH_2O \quad \textbf{(4)}$$

The two phases behave differently. C_3S, which hydrates quickly, carbonates mainly indirectly, whereas C_2S reacts more directly with CO_2 and does so faster (reaction rate 41.67 for C_2S vs. 21.39 for C_3S) (Gong et al., 2025) . Due to the fast hydration rate of C_3S, most carbonates form through the interaction of C_3S hydration by-products with CO_2. In contrast, C_2S primarily reacts directly with CO_2.

The microstructural outcomes differ correspondingly: carbonated C_3S forms a denser matrix with a self-limiting surface barrier (depth of about 1 mm at 14 days), while carbonated β-C_2S forms a looser, more penetrable matrix with deeper carbonation and the most pronounced pore-filling effect of the clinker phases. C_3A and C_4AF, by contrast, show low carbonation reactivity, with no significant change in porosity or degree of reaction under carbonation treatment (Sun et al., 2025).

The differential reactivity of C_3S versus C_2S explains why concrete of different clinker composition (and therefore different C_3S:C_2S ratio) can show different carbonation depth and uptake under nominally identical treatment conditions, a source of scatter in the data that is rarely controlled for explicitly in the primary studies (Gong et al., 2025).

3.5 Polymorph Control: Calcite, Vaterite, and Aragonite

$CaCO_3$ crystallises as calcite (most stable), aragonite (metastable), or vaterite (least stable), with the balance set by temperature, CO_2 concentration, and moisture (Han et al., 2025) . Calcite dominates under most conditions and is favoured by higher temperature, lower CO_2 concentration, and available water, and is the primary $CaCO_3$ polymorph in carbonated C_3S and C_2S pastes.

Vaterite forms preferentially in carbonated C_3A/C_4AF binders and during C-S-H carbonation, and can be stabilised by specific ions or organic modifiers; it is primarily observed in carbonated C_3A and C_4AF pastes (Sun et al., 2025) . Aragonite is favoured by higher CO_2 concentration and Mg^{2+} presence. (Park et al., 2025) observed aragonite dominance at 10% CO_2 versus a vaterite/aragonite mix at 3% CO_2. Polymorph ratio affects performance: aragonite and vaterite both improve composite compressive strength to a degree that depends on their relative proportion (Park et al., 2025), and selective polymorph synthesis from recycled cement paste powder has been demonstrated using ammonia, $Mg(OH)_2$, and glycine as crystallisation modifiers (Han et al., 2025) . Table 3 summarises the stability, morphology, and performance effects of the three polymorphs.

Table 3 : Comparison of $CaCO_3$ Polymorphs Formed During CDW Carbonation (Han et al., 2025; Park et al., 2025; Sun et al., 2025)

Polymorph	Stability	Morphology	Favourable Conditions	Effect on Performance
Calcite	Most stable	Rhombohedral crystals	Higher T, lower CO_2, presence of water	Dense microstructure; good mechanical properties
Aragonite	Metastable	Needle-like crystals	Higher CO_2 concentration; Mg^{2+} presence	Improved bond strength; enhances ITZ
Vaterite	Least stable	Spherical crystals	C_3A/C_4AF binders; certain ions/modifiers	Pozzolanic reactivity; nano-size beneficial

3.6 Carbonation of Ettringite and Other Phases

Ettringite also carbonates, forming calcium carbonate and gypsum, with implications for the dimensional stability of carbonated products (Kangni-Foli et al., 2021) . In calcium sulfoaluminate cement systems, carbonation-cured CSA cements have been explored to elucidate their durability aspects and potential opportunities for practical applications (Park et al., 2025) .

Net micropore-structure change in carbonated cement paste reflects a competition between two opposing effects: capillary-pore clogging by $CaCO_3$, and new capillary porosity generated by C-S-H decalcification.

4. Accelerated Carbonation Methods Applied to CDW

4.1 Classification Framework

Accelerated carbonation methods for CDW are classified by physical state (gas-solid vs. aqueous) and degree of CO_2 pressurisation (Shuvo et al., 2024) . (Shuvo et al., 2024) distinguish four principal methods (standard (SC), pressurised (PC), flow-through (FC), and wet carbonation (WC) while (Ali et al., 2026) , synthesising 124 peer-reviewed studies, assessed how relative humidity, temperature, CO_2 concentration, and duration affect mechanical and durability outcomes across these same four modalities. RILEM TC 309-MCP's classification adds a further physical distinction (moist flow-through, pressurised moist, aqueous, moist rotating drum, and moisture-conditioned rotating drum methods) which frames the method-by-method treatment below (Villagran-Zaccardi et al., 2024) .

The six method families are not interchangeable engineering choices so much as points along two underlying continua: how much external energy is invested to overcome the diffusion barrier that a carbonated shell otherwise creates, and how much the aggregate is mechanically disturbed during treatment. Atmospheric and flow-through carbonation invest little energy and leave the particle mechanically undisturbed, which is why they remain slow and diffusion-limited; pressurised carbonation invests substantial energy to force CO_2-laden fluid through that same barrier; rolling/drum carbonation instead removes the barrier mechanically as it forms; and aqueous/wet carbonation sidesteps the barrier altogether by dissolving the reactive calcium directly into solution (Shuvo et al., 2024) . Viewed this way, the apparent trade-off in Table 4 between uptake and technology readiness is not a coincidence of the current literature but a structural consequence of which lever each method pulls: the fastest routes are fast precisely because they spend energy or mechanical work that the slower, more mature routes do not.

Table 4. Comparative Overview of Accelerated Carbonation Methods for CDW*(*Ding et al., 2023*;* dos Reis et al., 2020*;* Fang et al., 2021*;* Sousanabadi Farahani et al., 2025*)* (Bao et al., 2026; Gholizadeh-Vayghan & Snellings, 2022*);* (Shuvo et al., 2024; Villagran-Zaccardi et al., 2024).

Table 4 : Comparative Overview of Accelerated Carbonation Methods for CDW (Ding et al., 2023; dos Reis et al., 2020; Fang et al., 2021; Sousanabadi Farahani et al., 2025) (Bao et al., 2026; Gholizadeh-Vayghan & Snellings, 2022); (Shuvo et al., 2024; Villagran-Zaccardi et al., 2024)

Method	Typical Conditions R	epresentative Performance Tr	eatment Time Bes	t-Suited Fraction Tech	nology Readiness / Key Trade-off
Atmospheric (standard)	5–100% CO_2; RH 50–70%; 20–30°C	Slowest uptake per unit time; most-studied baseline	Days to weeks	Coarse RCA, RMA	Mature, low-cost, but throughput-limited

Pressurised	0.05–0.30 MPa (optimum ~0.30 MPa)	30% and 42% gains in compressive and split-tensile H strength vs. untreated RCA concrete	ours C	oarse RCA (10–20 mm) P	ilot/industrial scale; cracking risk above 4–8 MPa
Flow-through	Continuous CO_2 flow; 60°C with wastewater pre-wetting	Processing time reduced from ~72 h to ~18 h with ~ wastewater pre-wetting	18 h (optimised) Co	arse and fine RCA Be	nch/pilot scale; benefits from ready-mix wastewater valorisation
Rolling/drum	Atmospheric to 1.4 bar; continuous tumbling s	Mass gain rising from 5.0 to 47.5 mg CO_2/g from Co tatic to 1.4 bar rolling	ntinuous Co	arse RCA Su	ited to continuous industrial processing; adds particle-rounding benefit
Aqueous/wet	0.5 bar CO_2 overpressure; 80°C; slurry	13.2% (cement substitute) and 9.0% (fine-aggregate substitute) strength gain in 6 h	~6 h R	CF and CDW fines F	astest per-unit-time efficiency; performance can decline if extended too long
Supercritical CO_2	>7.38 MPa, >31.1°C 1	64% increase in carbonation depth; 47% compressive Ho strength gain; up to 96.1 kg CO_2/m^3 uptake	urs (rapid) Hi	gh-value structural Hi applications	ghest performance ceiling; highest energy and equipment cost

4.2 Atmospheric Carbonation

Standard carbonation at 5–100% CO_2 is the most widely studied approach, owing to its operational simplicity and compatibility with commercial CO_2 chambers. Moisture control is critical. Sufficient pore water is needed to dissolve CO_2 and mobilise Ca^{2+}. Excess moisture, however, blocks diffusion (Gholizadeh-Vayghan et al., 2020) . (Ali et al., 2026) identify RH 50–70%, 20–30°C, and 20–50% CO_2 as the optimal window across the studies they reviewed; China's standard test protocol (GB 50082) specifies 20% ±3% CO_2, 70% ±5% RH, 20 ±2°C (Gomes et al., 2023) . Standard carbonation reduces porosity most effectively over long durations but is generally too slow for practical throughput, which motivates the pressurized and aqueous methods below (Ali et al., 2026).

4.3 Pressurised Carbonation

Elevated CO_2 partial pressure increases pore-water CO_2 solubility, driving deeper penetration through the outer carbonated shell that otherwise limits standard carbonation (Ding et al., 2023) . (Ding et al., 2023) tested coarse RCA (10–20 mm) at 0.05–0.30 MPa and found apparent density, water absorption, and crushing value all improving exponentially with pressure, optimal at 0.30 MPa, with SEM/TG-DSC confirming more extensive OITZ carbonate filling at higher pressure. Independently, (Sousanabadi Farahani et al., 2025) applied 5–60 psi to highway-demolition RCA and found 40–60 psi combined with ~55% RH optimal in both lab- and large-scale trials, yielding 30% and 42% gains in compressive and split-tensile strength for the resulting concrete versus untreated RCA concrete. Several studies converge on 4–8 MPa as the ceiling beyond which new cracking in the attached mortar can offset the gains (Ding et al., 2023; Sousanabadi Farahani et al., 2025) .

4.4 Flow-Through Carbonation

Continuous CO_2 flow through the aggregate bed prevents localised gas depletion and gives more consistent particle-to-particle exposure than static atmospheric carbonation (Shuvo et al., 2024) . (Fang et al., 2021) combined flow-through carbonation with a pretreatment spray of Ca^{2+}-rich wastewater reclaimed from ready-mix concrete batching plants, finding that pre-wetting RCA to 60% of its 24-hour water absorption capacity with this wastewater, followed by 12 hours of air drying and 6 hours of carbonation at 60°C, reduced total processing time from the 72 hours typical of earlier flow-through protocols to about 18 hours while still improving microhardness and reducing water absorption. This matters practically for three reasons: it valorises a wastewater stream that ready-mix plants would otherwise need to treat and dispose of, it supplies additional Ca^{2+} that a plain water spray would not, and it demonstrates that flow-through carbonation's main historical drawback can be substantially closed without resorting to pressurisation (Fang et al., 2021).

4.5 Rolling and Drum Carbonation

Rolling carbonation combines mechanical abrasion with chemical reaction: continuous tumbling exposes fresh reactive surface as the carbonated shell wears away (dos Reis et al., 2020). (dos Reis et al., 2020) report mass gain rising from 5.0 mg CO_2/g under static conditions to 23.0 mg CO_2/g under rolling at atmospheric pressure, and to 47.5 mg CO_2/g at a modest 1.4 bar. With phenolphthalein testing confirming full cross-sectional carbonation of particles ≥6 mm at the optimum condition. A useful secondary effect is particle rounding, which may improve workability (dos Reis et al., 2020). RILEM TC 309-MCP documents both moist and moisture-conditioned rotating-drum variants as established approaches, and the method's combination of carbonation with mechanical beneficiation suits continuous industrial processing (Villagran-Zaccardi et al., 2024) .

4.6 Aqueous and Wet Carbonation

Processing CDW fines as a slurry accelerates calcium dissolution relative to gas-solid contact, giving higher carbonation degree per unit time. Under 0.5 bar CO_2 overpressure at 80°C, (Gholizadeh-Vayghan & Snellings, 2022) achieved peak CO_2 uptake and the largest porosity/absorption reductions, with only 6 hours of treatment sufficient to raise compressive strength by 13.2% (as cement substitute) and 9.0% (as fine-aggregate substitute) relative to untreated fines. Wet carbonation reaches a given efficiency fastest of all methods but can lose performance if extended too long, likely through re-dissolution of already-formed carbonation products (Shuvo et al., 2024) .

4.7 Supercritical CO_2 Carbonation

Above 7.38 MPa and 31.1°C, CO_2 combines liquid-like density with gas-like diffusivity, sharply accelerating reaction kinetics. Under supercritical conditions (7.5 MPa). (Bao et al., 2026) recorded a 164% increase in carbonation depth and a 47% gain in compressive strength for low-carbon recycled concrete relative to atmospheric-pressure (0.1 MPa) treatment, alongside a 28–34% reduction in porosity as flocculent C-S-H gel converted to $CaCO_3$ — with maximum carbon uptake reaching 96.1 kg CO_2/m³. The obvious barrier is energy cost: pressurisation and specialised equipment make this method best suited to high-value applications where rapid, maximal treatment justifies the expense (Bao et al., 2026) .

4.8 Carbonation of Recycled Masonry and Mixed Aggregates

RMA/MRA carbonation remains understudied relative to their real-world abundance (Dulshi Peiris et al., 2025). (Suescum-Morales et al., 2021) cured fresh, porous cement-based products at 0/50/100% RMA sand replacement under two regimes (ambient ~0.04% CO_2 versus a 5% CO_2 chamber), finding accelerated carbonation improved mechanical strength and dry bulk density while reducing curing time needed to reach optimal strength, with CO_2 sequestration capacity reaching approximately 27 kg CO_2 per tonne of cement-based product in the RMA-containing mixes. (Merino-Lechuga et al., 2023) found carbonation curing of vibro-compacted porous

CDW concrete increased dry bulk density and compressive strength while shortening set time, with RCA reaching a maximum capture ratio of 52.52 kg CO_2/t. (Bastos et al., 2024) , working with realistically service-aged (partially pre-carbonated) CDW, found MRA reached peak uptake fastest (5 h vs. 12 h for RCA, at 23°C/60% RH/25% CO_2) but still captured a substantial 123–225 kg CO_2/t cement paste, versus 52–491 kg CO_2/t for RCA.

5. Effects of Carbonation on CDW Aggregate Properties

Building on the reaction chemistry established in Section 3, this section quantifies the resulting physical, mechanical, and microstructural changes. Improvement magnitude depends on carbonation duration, pressure, gas flow, and particle size ((Ding et al., 2023; Mehmood et al., 2025) . Carbonation systematically improves the physical, mechanical, and microstructural properties of CDW aggregates through $CaCO_3$/silica-gel precipitation and ITZ densification (Zhan et al., 2020) The property changes reported come from research groups working independently, in different countries, on different source concrete, using different carbonation rigs — yet the direction of every reported effect is consistent: water absorption falls, density rises, crushing value improves, and the ITZ densifies (Leemann et al., 2023; Lei et al., 2025). That directional consistency across an otherwise heterogeneous evidence base is a strong form of validation, and it is the main reason this review treats the underlying mechanism (Section 3) as well-established (Zhang et al., 2025) .

5.1 Water Absorption

Moisture regime during treatment is decisive: carbonation at >95% RH produces essentially no drop in absorption, while preconditioning at ≤95% RH yields reductions of up to 27% (Gholizadeh-Vayghan et al., 2020) . Pressurised treatment adds a further, independent lever. (Ding et al., 2023) found water absorption, density, and crushing value all improving with pressure up to 0.30 MPa, reaching a substantially larger reduction than atmospheric treatment alone at that optimum. Pre-soaking in limewater before carbonation outperforms direct treatment again, at 22.9% absorption reduction, because the extra dissolved Ca^{2+} accelerates $CaCO_3$ precipitation (Yajing et al., 2025). The FastCarb project separately found that sand-fraction RCA captures roughly twice the CO_2 of coarser fractions per unit mass, and that ambient-condition sensitivity was as important to net benefit as the carbonation chemistry itself (Torrenti et al., 2022) .

5.2 Density and Porosity

Solid-phase volume increases by approximately 3% during carbonation as $CaCO_3$ and silica gel occupy former pore space, translating into apparent density gains of 1.5–5.0% across the studies synthesised here. (Ding et al., 2023) recorded a 2.5% density increase at the 0.30 MPa optimum; the limewater pre-soak route reached 4.1% (Yajing et al., 2025).

5.3 Mechanical Properties: Crushing Value and Microhardness

Crushing value improves by 10–25% under optimised atmospheric carbonation (Ali et al., 2026) and exponentially with pressure up to the same 0.30 MPa optimum identified above, with Vickers microhardness gains concentrated at the OITZ rather than the bulk attached mortar, consistent with preferential calcite formation at that interface (Ding et al., 2023) . (Gholizadeh-Vayghan et al., 2020) further confirmed that mechanical property improvements under carbonation are highly dependent on moisture regime, with optimal preconditioning yielding the largest gains.

5.4 Microstructural and Nanomechanical Evidence

At the microscale, SEM-BSE, XRD, TGA, and MIP consistently confirm the calcite/silica-gel precipitation sequence described in Sections 3.2–3.3, with the ITZ as the primary site of change (Leemann et al., 2023).

(Leemann et al., 2023) identified $CaCO_3$ and decalcified C-S-H as the principal alteration products under 100% CO_2 exposure.

At the nanoscale, (Lei et al., 2025) provide the most granular quantification available for the bond between carbonated recycled aggregate and new cement paste, reporting substantial reductions in ITZ micropore content and thickness alongside gains in local elastic modulus. Complementary molecular dynamics simulation of a carbonated ITZ system found consistent large relative gains at the atomistic level and showed that the densified nanopore structure resists ion leaching in erosive environments, improving chemical durability as well as mechanical strength (Tang et al., 2025) . Taken together, these two studies indicate that the macroscale improvements reported in Sections 5.2–5.4 are not simply a bulk pore-filling effect but are underpinned by genuine strengthening of the atomic-scale bonding at the old-new interface, an important distinction, since a purely pore-filling mechanism would be expected to saturate quickly and offer little resistance to sustained mechanical or chemical loading, whereas an interfacial-bonding mechanism should be more durable under the sustained loading and exposure conditions the material will actually experience in service (Lei et al., 2025; Tang et al., 2025).

6. Performance of Concrete and Mortar Incorporating Carbonated CDW

Incorporating carbonated CDW aggregate into concrete or mortar yields systematic improvements in mechanical properties and durability, through a combination of reduced internal water demand (lower aggregate water absorption), $CaCO_3$ nucleation effects on new hydration products, and densification of the new ITZ between carbonated aggregate and fresh cement paste (Poon et al., 2023) .(Dulshi Peiris et al., 2025), synthesising findings from over 150 studies, found that carbonation — alongside polymer impregnation and nano-silica treatment — consistently improves density, strength, and chloride resistance, making carbonated recycled concrete viable for both structural and non-structural applications. The RILEM Technical Committee 309-MCP's review reaches a similar conclusion while stressing that significant techno-economic challenges remain for upscaling (Villagran-Zaccardi et al., 2024) .

6.1 Mechanical Properties

Compressive strength. (Jamil et al., 2025) carbonated 10–20 mm recycled aggregate at 1 bar for 2 hours and found the resulting concrete (CRAC) gained 30% compressive strength over conventional RAC, alongside a 1.5% density increase and reduced water absorption (6.0% vs. 7.58%).(Russo & Lollini, 2022), working with coarse RCA across a 0.45–0.55 water-to-cement ratio range, found more modest but still consistent gains of 7–15% at 28 days. Optimal carbonation conditions for maximising this benefit, RH 50–70%, 20–30°C, CO_2 20–50% are as identified in Section 2.8, consistent with the pressure and humidity optimum reported independently by (Sousanabadi Farahani et al., 2025) .

Split tensile and flexural strength. (Jamil et al., 2025) recorded a 42% increase in split tensile strength for CRAC over conventional RAC, while(Mozumder et al., 2025) report flexural-strength gains of up to 28% for properly carbonated RCA concrete. Both improvements trace to the calcite nucleation layer that forms on the carbonated aggregate surface, which strengthens bonding with the new cement paste and densifies the new ITZ (Zhan et al., 2020).

6.2 Durability Properties

Transport properties. Densification of the pore structure improves transport resistance across the board (Zhang et al., 2025). A cross-study review focused specifically on durability found that, while most durability indicators of carbonated-RCA concrete remain below those of natural-aggregate concrete, every durability indicator improves by 13–55% relative to non-carbonated recycled-aggregate concrete, attributable to the densified post-carbonation microstructure (Zhang et al., 2025) . (Jamil et al., 2025) water-absorption reduction is paralleled by sorptivity reductions of 40–45% and carbonation-coefficient reductions of 16–21% reported for durable low-carbon RAC (Xuan et al., 2017). (Xuan et al., 2017) 's systematic durability assessment of

carbonated-RCA concrete additionally found improved chloride-ion penetration resistance. For fully recycled concrete using carbonated fine aggregate, (Jean et al., 2024) found a 50% reduction in chloride permeability coefficient relative to untreated fine aggregate.

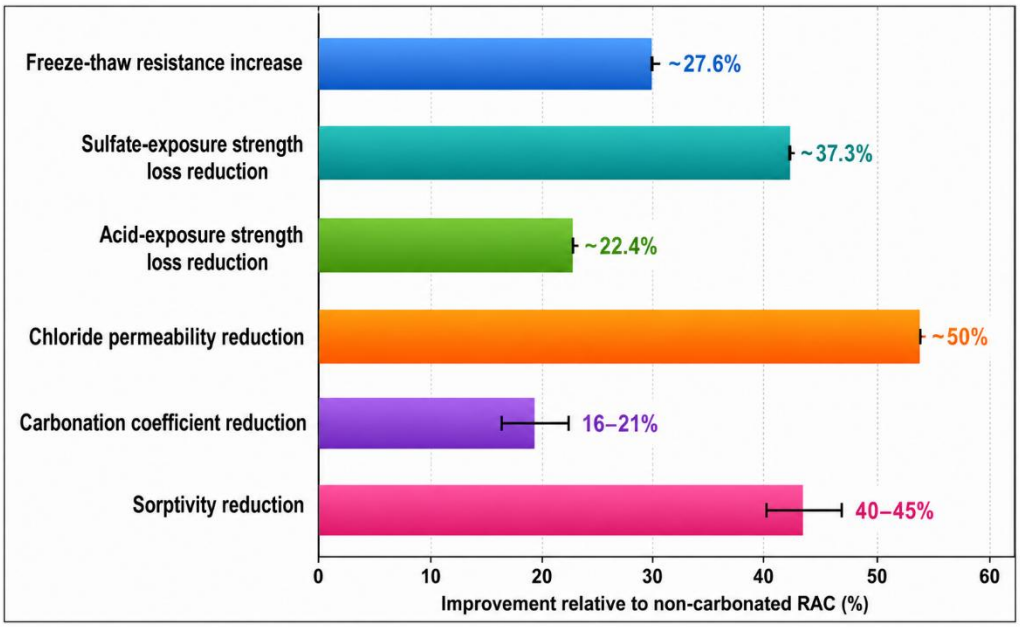

Figure 2 : Durability improvements of carbonated recycled aggregate concrete (CRAC) compared to conventional recycled aggregate concrete (RAC). Data compiled from (Jamil et al., 2025; Jean et al., 2024; Xuan et al., 2017; Zhang et al., 2025).

Chemical resistance. In 90-day acid-exposure testing, (Jamil et al., 2025) found CRAC's strength loss limited to 37.9% (vs. 48.85% for RAC) and weight loss to 5.4% (vs. 10.92%); in 150-day sulfate exposure, the corresponding reductions were 19.7% vs. 31.4% (strength) and 2.2% vs. 3.6% (weight).

Freeze-thaw resistance. (Jean et al., 2024) recorded a 27.6% increase in freeze-thaw resistance for fully recycled concrete with 100% carbonated fine aggregate. For field assessment, (Mozumder et al., 2025) evaluated the Super Air Meter as a practical freeze-thaw resistance test for carbonated RCA concrete in transportation infrastructure. Figure 2 summaries these durability gains across the four independent datasets discussed above.

6.3 The Alkalinity-Durability Trade-off

The most significant unresolved durability concern for carbonated CDW concrete in reinforced applications is the tension between two simultaneous effects: improved transport resistance (good) and reduced pore-solution pH (concerning for steel passivation), first identified systematically by(Xuan et al., 2017) .(Zhan et al., 2019) confirmed the mechanism directly in mortar: carbonation reduced water absorption, sorptivity, RCPT charge passed, chloride diffusion coefficient, and bulk conductivity, but pH fell from roughly 12.5 to below 9. (Mozumder et al., 2025) quantified a comparable aggregate-level pH drop (approximately 12.0 to below 9.8), noting the same reduction that mitigates alkali-silica reaction risk also reduces protective alkalinity. (Jamil et al., 2025) further found that combining carbonated RCA with supplementary cementitious materials compounds this effect, since both consume calcium hydroxide. Resolving this trade-off remains an open research priority. The most promising route is likely an integrated electrochemical assessment that evaluates transport resistance alongside corrosion potential (Zhan et al., 2019).

It is worth being explicit about why this trade-off has proven so persistent in the literature rather than simply being engineered around. Every mechanism that makes carbonation beneficial for transport resistance operates by consuming the same alkaline reserve that protects reinforcement. This applies to portlandite consumption, pore-filling calcite precipitation, and ITZ densification alike (Sections 3.2, 5.3–5.4) (Xuan et al., 2017; Zhan et al., 2019). There is, in other words, no obvious formulation lever that captures the transport benefit while leaving

the alkalinity untouched, because the two outcomes share a common chemical cause (Zhan et al., 2019) . This is different from most durability trade-offs in concrete technology, which typically involve independent mechanisms that can in principle be decoupled through mix design. Practical mitigation therefore likely lies not in avoiding the trade-off but in bounding it: partial rather than complete carbonation of the aggregate (leaving a reactive alkalinity reserve in the uncarbonated core), carbonating only the fractions used in non-reinforced or non-structural applications, or pairing carbonated aggregate with corrosion-inhibiting admixtures in reinforced applications (Villagran-Zaccardi et al., 2024). None of these has yet been systematically evaluated against the electrochemical endpoint that actually matters: time-to-depassivation under realistic chloride or carbonation-front exposure. This is precisely the gap Section 8.3 flags as a high-priority research need.

7. CO_2 Uptake Quantification and Environmental Assessment

Accurate, reproducible quantification of CO_2 uptake is fundamental to evaluating the environmental benefit of CDW carbonation and to supporting standardised reporting. RILEM TC 309-MCP has emphasised that accurate measurement of CO_2 content and uptake in cement-based and other construction products is essential for the development and certification of novel mineral carbonation products, processes, and practices. Measurement is nonetheless complex: samples range from fine powders to blocks with varying heterogeneity, different solid carbonate phases can be present, and measurement methods may require correction for interferences (Matschei et al., 2026) .

7.1 Measurement Methods

Thermogravimetric analysis (TGA) measures the mass loss attributed to $CaCO_3$ decomposition in the 600–900°C range, distinguished from lower-temperature events associated with C-S-H dehydration (100–400°C) and $Ca(OH)_2$ dehydroxylation (~450°C); pre- and post-carbonation TGA data allow direct calculation of the $CaCO_3$ mass increase, proportional to CO_2 fixation (Gomes et al., 2023) .

Table 5: Comparison of CO_2 Uptake Measurement Methods (Ding et al., 2023; dos Reis et al., 2020; Gomes et al., 2023; Matschei et al., 2026)

Method	Principle	Advantages	Limitations
Thermogravimetric Analysis (TGA)	Mass loss from $CaCO_3$ decomposition (600–900°C)	Quantifies specific carbonate phases; distinguishes from other decomposition events	Sample size limitations; overlapping events possible
Combustion Analysis	High-temperature oxidation; CO_2 measurement	Simple; high throughput	Does not distinguish carbonate sources
X-ray Diffraction (XRD)	Rietveld quantitative phase analysis	Phase-specific; non-destructive	Requires careful sample preparation; detection limits
Wet-Chemical Analysis	Acid digestion; CO_2 evolution measurement	Direct measurement; low cost	Time-consuming; potential sample loss
Phenolphthalein Test	pH indicator mapping	Simple; visual; depth measurement	Qualitative; limited to pH mapping

Combustion analysis determines carbon content by oxidizing a sample at high temperature and measuring evolved CO_2, particularly suited to samples where carbonate phases are the primary carbon-containing species. X-ray diffraction with Rietveld quantitative phase analysis provides precise phase-proportion measurement for well-characterized laboratory specimens. Wet-chemical analysis (acid digestion followed by CO_2 evolution measurement) provides an alternative approach (Matschei et al., 2026) .

The phenolphthalein indicator test assesses carbonation-penetration depth by mapping pH reduction below ~9 on a freshly fractured surface; it is qualitative but standardly referenced in EN 14630 and particularly useful for

confirming full cross-sectional carbonation of aggregate particles (dos Reis et al., 2020; Gomes et al., 2023) . Table 5 compares these five methods by principle, advantages, and limitations.

7.2 CO_2 Uptake Values and Determinants

Reported uptake spans more than an order of magnitude across CDW fractions and treatment routes, from approximately 27 kg CO_2/t cement-based product for RMA-containing mixes under ambient-pressure chamber curing to over 490 kg CO_2/t cement paste for finely ground, highly reactive RCA under optimised conditions (Suescum-Morales et al., 2021) ; (Bastos et al., 2024) . At the aggregate level,(Bastos et al., 2024) found RCA captured 52–491 kg CO_2/t cement paste (peak uptake at 12 hours) versus 123–225 kg CO_2/t for MRA (peak at 5 hours), reflecting RCA's higher reactive-calcium content. For RCF, theoretical carbonation potential reaches 14.0 g CO_2/100 g RCF, with wet carbonation achieving 8.48 g/100 g (60.6% of theoretical) after 120 minutes. The FastCarb project reported approximately 30 kg CO_2/t crushed concrete under industrial-scale atmospheric conditions (Torrenti et al., 2022). For RMA-containing mixes, CO_2 sequestration capacity reaches approximately 27 kg CO_2 per tonne of cement-based product (Suescum-Morales et al., 2021). At the sector level, independent global carbon-accounting places cumulative cement-carbonation CO_2 uptake at roughly 250 Mt CO_2/year worldwide as of 2024, offsetting an estimated 10% of annual process emissions from clinker production (Niu et al., 2025) . The principal determinants of uptake magnitude are cement paste content, pre-existing natural carbonation, moisture, CO_2 concentration, pressure, temperature, and particle size (Bastos et al., 2024) . Figure 3 illustrates how uptake varies across CDW fractions and treatment methods.

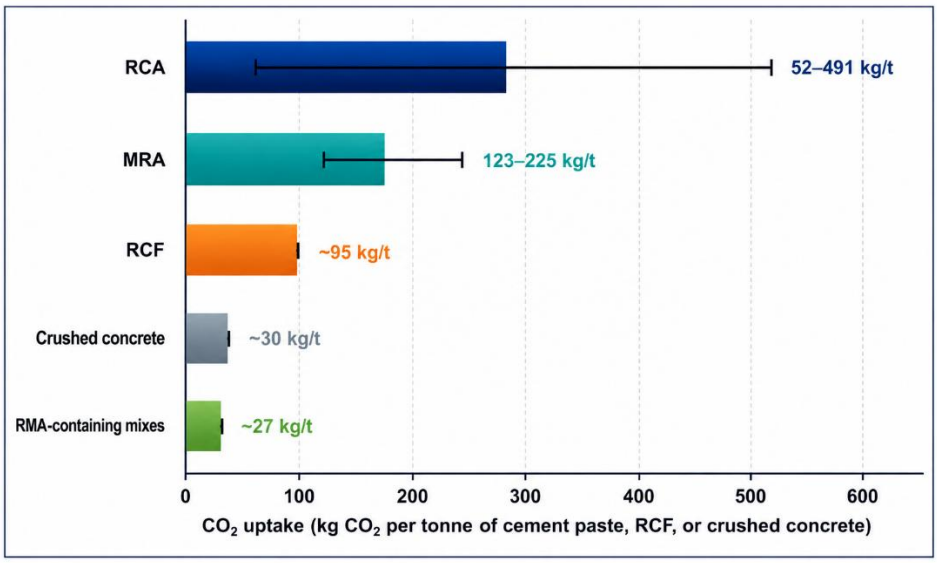

Figure 3 :CO_2 uptake by CDW fraction and treatment method. Data compiled from (Bastos et al., 2024) ; (Gholizadeh-Vayghan & Snellings, 2022; Torrenti et al., 2022);(Suescum-Morales et al., 2021).

7.3 Life Cycle Assessment Framework

Global Warming Potential (GWP) results for unbound material ranging from −48 to +14 kg CO_2e/t, a wide spread traced to inconsistent system boundaries, unclear multifunctionality handling, and conflation of avoided emissions with genuine carbon removals (Belizario-Silva et al., 2026). Addressing exactly these inconsistencies, (D. Peiris et al., 2025) conducted an integrated cradle-to-gate LCA with Module D credits and cost analysis across eight strength-standardised Australian concrete mixes, finding carbonated RAC achieved the lowest GWP (27% below natural-aggregate concrete) and lowest production cost of any option tested, with cement-slurry-treated RAC a secondary best performer (11% GWP reduction). Module D credits showed virgin-aggregate concrete scoring negative on circularity while every recycled-aggregate variant scored positive, carbonation and pozzolanic coatings performing best (Dulshi Peiris et al., 2025). Separately, (Feng & Xian, 2025) reached a

similar environmental-and-cost conclusion for Hong Kong specifically, linking fundamental carbonation research directly to LCA outcomes.

7.4 Regional Variability

Environmental and economic benefit varies substantially by region, driven mainly by grid carbon intensity and aggregate supply-chain emissions (Pu et al., 2023). (Pu et al., 2023), valuating 14 global regions with integrated LCA and life-cycle costing, found the CO_2 benefit ratio ranging from 0.7 (Brazil) to 2.6 (Pakistan) and economic benefit ranging from +18.5 USD/t (USA) to −5.6 USD/t (Pakistan) — meaning only a subset of regional contexts achieve net CO_2 negativity and positive economic value simultaneously, underscoring that process optimisation and CO_2-source selection are prerequisites for commercial deployment (Pu et al., 2023) . (Belizario-Silva et al., 2026) further noted that system boundary choices significantly affect regional LCA outcomes, with different studies adopting different conventions for avoided burdens and credit allocation.(Dulshi Peiris et al., 2025) provided a detailed Australian case study demonstrating how Module D credits can substantially improve the circularity profile of carbonated RAC in a specific regional context. (Feng & Xian, 2025) similarly demonstrated regional specificity for Hong Kong, showing that local grid carbon intensity and aggregate transport distances materially affect net GWP outcomes.

7.5 Circular Economy and Policy Implications

Mineral carbonation of CDW aligns directly with EU Green Deal and Waste Framework Directive circularity objectives. The EU's headline 88–89% CDW recovery rate substantially overstates high-value recycling, since it includes large volumes of low-grade backfilling (Caro et al., 2024) — carbonation offers a technically demonstrated route to upgrade CDW to structural-concrete-grade quality, a materially higher-value outcome than road sub-base or backfill use (Caro et al., 2024) . At the sector scale, recent global analysis estimates the theoretical CO_2 storage potential of engineered carbonation across all building materials (not CDW alone) at over 16 billion tonnes annually — several times current global cement-sector emissions — indicating substantial unexploited headroom for the pathway this review addresses, even though CDW-specific realised uptake today remains a small fraction of that ceiling(Van Roijen et al., 2025).

8. Standardisation, Research Gaps, and Future Directions

8.1 RILEM TC 309-MCP Contributions

RILEM Technical Committee 309-MCP ("Mineral Carbonation for the Production of Construction Materials") has made foundational contributions to the field. (Snellings & Matschei, 2025) published a terminology recommendation distinguishing accelerated from natural carbonation, CO_2 curing from pre-carbonation, and direct (gas-solid) from indirect (aqueous) pathways — a shared vocabulary prerequisite for comparing results across research groups. (Matschei et al., 2026), a 29-author committee effort, critically reviewed CO_2-mineralisation test methods (TGA, combustion analysis, XRD, wet-chemical analysis), detailing sample-preparation pitfalls and interference corrections for each. The committee's Working Group 1 separately reviewed 16 peer-reviewed LCA studies on carbonated RCA, recommending harmonised system-boundary and multifunctionality conventions(Belizario-Silva et al., 2026) . (Villagran-Zaccardi et al., 2024) techno-economic mapping of these same barriers established the scale of the gap between laboratory demonstration and commercial deployment.

8.2 Standardisation Gaps

No harmonised European standard currently exists for measuring CDW aggregate CO_2 uptake, characterising carbonation degree, or certifying carbonated aggregate for structural use. EN 13295 covers concrete carbonation resistance testing but not aggregate pre-treatment quantification; EN 933-11 classifies recycled aggregates but

does not address carbonation treatment. The most common accelerated-carbonation protocol in CDW research (Chinese standard GB 50082: 20% CO_2, 70% RH, 20°C) has no direct European equivalent. Round-robin testing across laboratories, as called for by (Matschei et al., 2026) test-methods review, is needed to establish repeatability before any of this can be standardised.

8.3 Research Gaps

Seven research gaps emerge from the preceding synthesis, clustered around a single underlying problem: the evidence base is built predominantly on small, well-characterised, laboratory-prepared RCA samples, whereas real deployment will involve heterogeneous, mixed, industrial-scale streams over multi-year service life.

- **Heterogeneous real-world CDW streams:** Most experimental work uses laboratory-prepared or pre-sorted RCA, not the mixed streams recycling plants actually process.
- **Alkalinity-durability trade-off:** Integrated electrochemical assessment combining transport resistance and corrosion potential is lacking. This gap is arguably the most consequential. It would not resolve itself simply by testing more realistic samples.
- **Long-term durability data:** Data beyond 5 years of service are scarce; most durability evidence comes from accelerated short-duration lab tests (Mozumder et al., 2025; Zhang et al., 2024) .
- **Industrial-scale process data:** Almost all published data are sub-kilogram batch-scale; continuous industrial carbonation introduces engineering parameters current studies do not address.
- **CO_2 source integration and economics:** Few studies couple CDW carbonation reactors directly to industrial flue-gas sources, and economic viability is highly source-dependent.
- **Harmonised measurement protocols:** No standardised protocol exists for measuring CO_2 uptake in CDW aggregates, making cross-study comparison difficult.
- **Masonry and mixed-waste fractions:** RMA, MRA, and gypsum-contaminated mixed CDW remain systematically under-studied relative to RCA.
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8.4 Research Roadmap

Short-term: round-robin CO_2-uptake measurement testing (Matschei et al., 2026) ; systematic characterisation of real-world (non-pre-sorted) CDW streams (Ali et al., 2026; Piccinali et al., 2022); integrated electrochemical alkalinity-durability assessment (Xuan et al., 2017; Zhan et al., 2019); LCA methodology refinement per RILEM TC 309-MCP recommendations(Belizario-Silva et al., 2026; Snellings & Matschei, 2025)

Medium-term: long-term (>5-year) durability studies (Zhang et al., 2024); industrial-scale continuous-process pilot plants (Shuvo et al., 2024) ; integration with flue-gas CO_2 sources(Belizario-Silva et al., 2026; Pu et al., 2023) standardised LCA methodology (Belizario-Silva et al., 2026) ;carbonated-aggregate certification protocols (Snellings & Matschei, 2025).

Long-term: commercial-scale deployment; full circular-economy framework integration; carbon-credit/emissions-trading scheme integration; supportive policy and regulatory frameworks; full life-cycle carbon accounting with Module D credits(Van Roijen et al., 2025).

9. Conclusions

This review synthesises 70 peer-reviewed publications on the mineral carbonation of construction and demolition waste. The technology offers a dual-purpose solution addressing both waste accumulation and carbon emissions, but the magnitude of benefit is conditional on well-characterised, single-fraction precursors under tightly controlled conditions. The **Key Findings found are:**

- Accelerated carbonation reduces RCA water absorption by up to ~35% under pressurised treatment, increases density by 1.5–5.0%, and improves compressive strength of recycled aggregate concrete by 7–33%.

- Carbonation improves transport resistance while reducing pore-solution pH from ~12.5 to below 9, removing the passivating alkalinity that protects embedded steel.
- Most experimental work uses laboratory-prepared RCA, yet real CDW is compositionally heterogeneous RMA/MRA. RMA and MRA remain systematically under-represented relative to their abundance.
- Uptake depends on cement paste content, particle size, and treatment conditions. Carbonated RAC achieves 27% lower GWP than natural-aggregate concrete, but regional variability is substantial.
- No harmonized European standard exists for CO_2 uptake measurement or aggregate certification. Highest research priorities: heterogeneous real-world streams, the alkalinity-durability trade-off, long-term durability, and industrial-scale process data.

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