European Commission

Support to the development of methodologies for the certification of industrial carbon removals with permanent storage

Review of carbon removals through mineral carbonation

Prepared by Cato Sandford, Chris Malins and Jonathan Lonsdale under service request CLIMATE-30420
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Submitted to:

European Commission
Directorate General for Climate Action
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By email: CLIMA-FWC-001@ec.europa.eu

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Review of carbon removals through mineral carbonation

A report submitted by ICF S.A, Cerulogy and Ecodiversity

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Contents

Executive summary

This technical report concerns the sequestration of CO_2 in the form of solid carbonate minerals on the surface of the Earth. We focus in particular on cement-based building materials, but also consider alkaline industrial wastes that contain carbonate-forming compounds.

Production of cement is intrinsically connected to CO_2 emissions. Lime (calcium oxide, CaO) is fundamental to the formation of strong bonds when the cement is hydrated to make concrete, but is too reactive to be found in nature and must be produced from limestone (calcium carbonate, $CaCO_3$) via a high-temperature 'calcination' process that drives off CO_2. Once the concrete made from the cement has hydrated and set, constituents such as portlandite (calcium hydroxide, $Ca(OH)_2$) and calcium-silicate-hydrate (C-S-H) may begin to react with CO_2 from the atmosphere to form calcium carbonate once again: this process is called 'recarbonation', and the resulting solid minerals represent a stable store of carbon. Similar considerations apply to the alkaline by-products of heavy industry that contain calcium oxide or calcium hydroxide[1].

Recarbonation of concrete and alkaline industrial wastes happens naturally at a rate that depends on its material characteristics and its environment. Thin mortar in a humid environment will recarbonate faster than large blocks that have been painted with a protective coating. Reactions will proceed slower in dense heaps of slag than in well aerated piles where water and CO_2 can penetrate more easily.

Treatments that artificially enhance CO_2 uptake can be termed 'active' or 'enhanced' recarbonation. Techniques to durably bind a concentrated stream of captured CO_2 into minerals could be deemed a form of carbon capture and sequestration (CCS), akin to geological storage pathways. When the CO_2 comes from direct air capture (DAC) or from biogenic sources, this form of storage could be considered for inclusion into the EU's Carbon Removals and Carbon Farming Certification Framework (CRCF). Enhanced recarbonation also encompasses practices that accelerate CO_2 absorption from ambient air, for example by disturbing slag piles to increase aeration.

Pre-cast concrete blocks which have been cured in a CO_2-enriched atmosphere, or carbonated aggregates that are added to cement mixtures, are examples of products that could be used in the construction industry while permanently sequestering CO_2. Active recarbonation can also be used for feedstocks that have reached the end of their primary use – for example demolition rubble or mine tailings. In these cases, physical and chemical treatments (e.g. crushing and solvent-based mineral extraction) can be used to further accelerate recarbonation.

For an active recarbonation project to generate CRCF credits, it would have to demonstrate that the carbon sequestration achieved through the project activities outweighs the sum of the project's process emissions plus any baseline sequestration that would have happened naturally. Some materials would reach their full carbonation state quickly without external intervention; if this natural recarbonation is included in the baseline term, then few or no permanent carbon removal units could be issued for an activity that involved active recarbonation of such materials. Quantifying baselines is a non-trivial exercise though, owing to the diversity of material structures and chemistries, and to the fact that the environment to which the material is exposed may change over the stages of its life-cycle.

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[1] Silicates and other alkaline compounds can also bind CO_2 into carbonates through a different mechanism. Such materials are said to undergo 'carbonation' rather than 'recarbonation', as there was no initial calcination step.

For example, a civil structure made of large reinforced-concrete blocks with a protective outer coating would ordinarily absorb relatively little CO_2 during its service life; but if that structure is demolished after 100 years and the crushed-up rubble is exposed to the elements, passive CO_2 uptake will accelerate significantly. In this case, an active recarbonation treatment of the building materials before they are used could offer a large net carbon sink for 100 years, but this would be at least partially offset thereafter as natural recarbonation catches up. While the mitigation of global warming for the initial 100 years has value (and could be quantified and rewarded), it would not meet the criteria of a permanent carbon removal under the CRCF, as counterbalancing a tonne of CO_2 emissions today requires a tonne of net CO_2 sequestration to be delivered and sustained on the time-scale of centuries at least.

The setting of baselines for active recarbonation practices therefore requires a counterfactual assessment to predict how much CO_2 would be passively absorbed by untreated materials. This contrasts with the situation for geological sequestration pathways, where no carbon would be sequestered in the absence of the project and the baseline can be set to zero. In the recarbonation context, there is a tension between stakeholders that would benefit from systematically high baselines and those that benefit from systematically low baselines: assuming high passive CO_2 uptake could serve to offset some of the cement industry's considerable carbon footprint, while assuming low passive uptake would amplify the benefits of active recarbonation treatments and generate more carbon credits for operators of those projects. Researchers, industry groups, and even national governments have proposed approaches for quantifying this baseline, while developers of active recarbonation technologies and certification bodies serving the voluntary carbon market have devised a range of methodologies for the generation of carbon credits. Consensus on the best approach does not seem likely to be immediately forthcoming.

Formulating a consistent approach to baselining for active recarbonation would be one of the critical issues for the European Commission to address if carbon storage in carbonate minerals was to be recognised under the CRCF. There is also a question as to whether end of life practices for cement and/or relevant industrial waste materials (such as regular disturbance to improve aeration) could be considered as permanent carbon removal activities in their own right. In any case, continued progress in materials science and engineering strives to deliver improvements in the carbon efficiency of cement and concrete[2]. Improving production methods in heavy industry may also influence the volume and nature of its alkaline by-products.

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[2] Though this will be hindered by dwindling regional availability of certain industrial by-products currently used as concrete additives.

1 Introduction

1.1 Policy context

On 19 November 2024, the European Council approved the EU certification framework for permanent carbon removals, carbon farming, and carbon storage in products (CRCF) (CRCF Regulation, 2024). This Regulation aims to boost innovative carbon removal technologies and sustainable carbon farming solutions by certifying high-quality carbon removals, and to contribute to the EU's climate, environmental, and zero-pollution goals. Moving forward, the Commission, supported by experts, will develop tailored certification methodologies for carbon removal activities delivering on climate and other environmental objectives.

To ensure the transparency and credibility of the certification process, the proposed regulation sets out rules for the independent verification of carbon removals, as well as rules to recognise certification schemes that can be used to demonstrate compliance with the EU framework. To ensure the quality and comparability of carbon removals, the proposed regulation establishes four QU.A.L.ITY criteria:

1. Quantification: Carbon removal activities need to deliver unambiguous benefits for the climate that can be measured and reported accurately;
2. Additionality: Carbon removal activities need to go beyond existing practices and what is already required by law;
3. Long-term storage: Certificates are linked to the duration of carbon storage and should ensure long-term storage on the time-scale of centuries;
4. Sustainability: Carbon removal activities must contribute to sustainability objectives such as climate change adaptation, circular economy, water and marine resources, and biodiversity.

In the CRCF, storage of carbon in products can be divided into two categories: carbon permanently chemically bound for at least several centuries; and ‘long-term’ but temporary carbon storage in products for at least 35 years. Permanently binding carbon in products may allow the issuance of permanent carbon removal credits, whereas long-term storage of carbon in products may allow the issuance of temporary carbon removal credits.

In 2024 the European Commission worked with a consulting team led by ICF to present to the EU’s Expert Group on Carbon Removals a draft specification for the certification of permanent carbon removal by DACCS and BioCCS. This draft specification was based on geological carbon storage at sites permitted under the CCS Directive (2018), where CO_2 extracted either from industrial sources or directly from the ambient air is injected underground in gaseous form. This paper discusses an alternative approach whereby removed carbon could be stored in solid mineral form. It also discusses the possibility of achieving carbon removal through actions that could encourage carbonate formation in end-of-life materials.

1.2 Carbon sequestration via carbonate minerals

Certain materials can bind CO_2 into their structure with strong and durable chemical bonds: either actively through exposure to concentrated CO_2 captured at dedicated facilities (i.e. from a concentrated source or from the atmosphere using DAC technology); or passively through absorption of atmospheric CO_2 during normal usage. The first, active, processes could provide an alternative to geological storage of CO_2; the second, passive, processes must be considered in assessing carbon removal baselines, but if practices could be adopted that would increase the CO_2 uptake by these passive processes this could be considered as a form of carbon removal. The active and passive pathways involve the same kinds of CO_2-absorbing materials: of particular interest are those which are produced at scale in the construction sector and heavy industries, and a prime example of this is cement and cement-based products.

Chemical processes generating carbonates from CO_2 are also relevant to other carbon removal pathways that are under consideration by the European Commission for inclusion in the CRCF – namely, enhanced rock weathering (ERW) and ocean alkalinity enhancement (OAE). In ERW and OAE, carbon is stored not as solid minerals but in aqueous form as bicarbonate and carbonate ions, ultimately reaching the long-term reservoir of the ocean. Nevertheless, there are overlaps in feedstock sourcing and contaminant mitigation; see Sandford et al. (2025) and Johnson et al. (2025) for reviews of these technologies submitted to the European Commission.

Permanent sequestration of CO_2 in materials – active or passive – is not at present widely represented in the carbon balance sheets of industrial producers or consumers. Nor is it generally represented in national greenhouse gas inventories, and there is no obligation to include it in annual reports to the United Nations Framework Convention on Climate Change (UNFCCC). The European Union is developing its approach in this regard: a recent update to the European Union's Emission Trading System (ETS) makes the following provision (European Union, 2024, Article 12):

> *"An obligation to surrender [ETS emission] allowances shall not arise in respect of emissions of greenhouse gases which are considered to have been captured and utilised in such a way that they have become permanently chemically bound in a product so that they do not enter the atmosphere under normal use, including any normal activity taking place after the end of the life of the product."*

Commission Delegated Regulation (EU) 2024/2620 (European Commission, 2024) specifies four types of material that are considered to permanently chemically bind CO_2 for the purpose of the ETS:

> *Mineral carbonates used in the following construction products:*
>
> *(a) carbonated aggregates used unbound or bound in mineral based construction products;*
>
> *(b) carbonated constituents of cement, lime, or other hydraulic binders used in construction products;*
>
> *(c) carbonated concrete, including precast blocks, pavers or aerated concrete;*
>
> *(d) carbonated bricks, tiles, or other masonry units.*

The IPCC (2005) similarly concluded that mineral-based construction materials of this sort – cement, concrete, etc. – can be treated as absorbing and durably retaining CO_2 under normal circumstances:

> *"Once the carbon has been stored through mineral carbonation, there are virtually no emissions of CO_2 due to leakage. … The fraction of carbon dioxide stored through mineral carbonation that is retained after 1000 years is virtually certain to be 100%."*

1.3 Baseline carbon removals

The CRCF Regulation (2024) quantifies net carbon removal (NCR) benefit of both permanent and temporary carbon removals with the equation:

$$NCR = CR_{baseline} – CR_{total} – GHG_{associated} \ ;$$

where,

> $GHG_{associated}$ refers to the increase in greenhouse gas emissions associated with the lifecycle of the carbon removal activity;
>
> CR_{total} refers to the total amount of permanent or temporary carbon removal delivered by the activity; and
>
> $CR_{baseline}$ refers to the amount of permanent or temporary carbon removal that would be delivered under a baseline scenario.

The baseline invoked by the last term must be “highly representative of the standard performance of comparable practices and processes in similar social, economic, environmental, technological and regulatory circumstances and take into account the geographical context, including local pedoclimatic and regulatory conditions”. In general, materials that can be actively made to absorb and store carbon through exposure to concentrated CO_2 are also subject to natural carbonation by CO_2 from the atmosphere. Whether and how potential natural carbonation of those materials should be reflected in the baseline carbon removal term is therefore an important consideration to be examined by this technical paper.

1.4 This paper

1.4.1 Scope

There are a few major dimensions that circumscribe the scope of this technical paper.

1. Carbon binding. We consider materials that are capable of absorbing CO_2 and binding it in the form of solid carbonate minerals such as calcium carbonate[3]. We focus on materials for which there is a ready supply, i.e. those that have the potential to sequester CO_2 at scale.
2. CO_2 source. Some pathways use carbonating materials to store concentrated CO_2 captured from the atmosphere or from a point source (this is akin to ‘conventional’ carbon capture with geological storage); other pathways enhance materials’ ability to absorb CO_2 from ambient air.
3. Material origin and fate. The material feedstocks under consideration include those that are purposefully produced and those that are by-products and wastes of heavy industries. The latter may go on to have second uses[4].

As we shall see, carbon removal certification methodologies for the voluntary market focus on various subsets of these options.

1.4.2 Terminology

Carbon removal is defined by the CRCF Regulation (2024) as:

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[3] It should be noted that these same ‘alkaline’ materials could in principle be used to neutralise acidity in terrestrial waters (soils, lakes, seas, etc.). This leads to a net draw-down of CO_2 which ultimately takes the form of dissolved bicarbonate and carbonate ions in the ocean. These aqueous pathways are addressed in the technical reports on enhanced rock weathering (Sandford et al., 2025) and ocean alkalinity enhancement (Johnson et al., 2025), and are not further considered here.

[4] For example concrete demolition waste can be used as infill or in roadbeds; but mine tailings containing toxic metals would have to be disposed of in the usual way.

> *"the anthropogenic removal of carbon from the atmosphere and its durable storage in geological, terrestrial or ocean reservoirs, or in long-lasting products"*

This paper follows the CRCF in using the term 'carbon' interchangeably with 'carbon dioxide' or 'CO_2', and also uses the terms 'carbon sequestration' and 'carbon storage' more or less interchangeably. The quantity of carbon sequestered is denominated in terms of the mass of CO_2 that would be formed by complete oxidation of the amount of carbon in storage.

Chemically binding carbon from CO_2 into long-lived molecules such as carbonates can be referred to as 'mineralisation' or 'carbonation'[5]. The term 'recarbonation' refers specifically to the case that CO_2 is re-absorbed into a material that previously released CO_2; we term the latter process 'decarbonation'[6], an important industrial example of which is calcination, where limestone is heated in a kiln to turn calcium carbonate into calcium oxide plus CO_2.

Many materials under consideration in this paper undergo a decarbonation step as part of their production, and are subsequently able to recarbonate. When recarbonation happens under normal conditions we can talk about 'natural' or 'passive' recarbonation. When materials are processed in a way that increases their uptake of CO_2 above the baseline level – for instance through exposure to a concentrated CO_2 stream, or having been treated to accelerate CO_2 absorption from ambient air – we refer to 'enhanced' or 'active' recarbonation.

Selected key terms are presented for reference in Table 1.1.

Table 1.1 Selected acronyms used in this report

Term	Definition
CCS	Carbon capture and sequestration
CH	Calcium hydroxide (portlandite)
C-S-H	Calcium-silicate-hydrate
CRCF	Carbon Removals and Carbon Farming Certification Framework Regulation
DAC	Direct air capture
DoC	Degree of carbonation
ERW	Enhanced rock weathering
ETS	EU Emission Trading System
GGBS	Ground granulated blast furnace slag
MPa	Megapascal
OAE	Ocean alkalinity enhancement

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[5] It should be noted that the term mineralisation may be used differently in in different contexts: for instance, in soils mineralisation may refer to a process that converts carbon from organic molecules into CO_2: this reduces rather than increases carbon storage. In this paper, however, mineralisation will always refer to the process of binding carbon into long-lived molecules.

[6] This is entirely distinct from 'decarbonisation' which refers to the reduction in emissions and/or emissions intensity from human activities, economic sectors, and national greenhouse gas inventories.

PCC	Precipitated calcium carbonate
PFA	Pulverised fly ash
RAAC	Reinforced autoclaved aerated concrete
RCA	Recycled concrete aggregate
SCM	Secondary cementitious material

1.4.3 Structure

This paper is organised as follows.

Chapter 2 identifies materials potentially offering permanent carbon storage in products, including concrete and industrial by-products. The recarbonation process and its sensitivity to material and environmental factors are described, with a focus on concrete, and active recarbonation methods introduced. Sustainability considerations are highlighted.

Chapter 3 presents a literature review of models and experimental investigations of natural recarbonation.

Chapter 4 provides an overview of existing standards to certify carbon removals by mineralisation/carbonation in materials.

Chapter 5 outlines some key considerations and challenges for implementing a crediting system under the CRCF.

2 Recarbonating materials

2.1 Cement and concrete materials

2.1.1 Cement overview

‘Cement’ is a term that can be used broadly to encompass many types of mineral-based materials with binding properties. Typically the term is used as a shorthand for Portland cement: a ‘hydraulic’ (i.e. water-activated) cement containing calcium silicates. It is produced from limestone and clay by heating. There are a number of sub-types of Portland cement, distinguished by the mix of production feedstocks, and hence by the chemical composition of the final cement product. In combination with ‘aggregate’ (e.g. sand, gravel, stones) and water, cement forms concrete. For some time after the ingredients are combined, the concrete mixture remains somewhat fluid and can be worked into the desired shape, but gradually becomes rigid (‘sets’) and then continues to harden and strengthen (‘cures’).

The cement industry is responsible for around 7% of anthropogenic greenhouse gas emissions (IEA et al., 2018), and demand for the material continues to grow globally (IEA, 2023). Cement production emissions arise from two main sources: the calcination of limestone (where calcium carbonate is exposed to high temperatures to drive off carbon dioxide, $CaCO_3 \rightarrow CaO + CO_2$) and from fuel combustion (needed to achieve the high kiln temperatures). The balance between these two sources depends on the details of the cement composition, the industrial fuel mix, and the energy efficiency of the facilities in question, but as a rule of thumb around 60% of cement production emissions come from calcination, and 40% from combustion of fossil fuels (Tanzer et al., 2021)[7].

Various initiatives have sought to reduce the greenhouse gas emissions of construction by diversifying building materials and improving the efficiency of cement usage (Cement Sustainability Initiative, 2005). Measures which have been recognised as creditable for the voluntary markets include the use of low-carbon components in the concrete mix (Riverse, 2024b; Scrivener et al., 2018; UNFCCC, 2012, 2024), reduction of fossil fuel use (UNFCCC, 2020), re-use of construction materials (Riverse, 2024a), and carbon capture at cement plants. An overview of decarbonisation options is given in Favier et al. (2018).

While cement production is a source of CO_2 emissions, cement-based materials, along with other industrial residues containing metal oxides and hydroxides, may naturally absorb ambient atmospheric CO_2 over time. This relies on the CO_2 being able to penetrate into the material, dissolve to form carbonate ions, and chemically react to form metal carbonate molecules. As remarked above, in the absence of external intervention this can be treated as permanent, as the metal carbonates are expected to be stable essentially indefinitely. Natural recarbonation therefore acts to counteract some of the emissions associated with material production; some stakeholders have called for this natural recarbonation to be explicitly recognised when assessing the carbon footprint of the industry.

Technologies and processes are under development to accelerate the uptake of CO_2 by building materials and mineral wastes from industry – we will return to these in Section 2.4.

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[7] Some sources say the split is more like 50:50 (e.g. Pade & Guimaraes, 2007). Capon & de Saulles (2023) estimate that in the UK in 2020, emissions from cement production were 3.9 $MtCO_2$ form calcination and 1.9 $MtCO_2$ from fuel combustion – about 67:33. This ratio is confirmed elsewhere (Favier et al., 2018).

2.1.2 Production processes

The raw materials for cement production are primarily calcium carbonate ($CaCO_3$) from limestone, and clay. Heating these materials in a kiln decomposes the calcium carbonate into calcium oxide (CaO) and carbon dioxide – the 'calcination' process. Calcium oxide reacts with silica, alumina, and iron compounds found in the clay to form 'clinker' minerals which are crushed to make cement powder. The composition of the cement powder determines the strength, setting time, and binding properties of the cement.

To produce concrete, cement is mixed with aggregates such as sand and gravel to give the concrete load-bearing compressive strength, with water to allow binding molecules and structures to form, and sometimes with supplementary cementitious materials (SCM), discussed below. Clinker minerals – in particular the calcium silicates alite and belite –undergo a series of hydration reactions to produce calcium hydroxide (abbreviated as 'CH' in cement industry notation and also known as portlandite) and calcium-silicate-hydrate (abbreviated as 'C-S-H'), among other compounds. The chemistry of CH and C-S-H determines many of cement's properties. CH forms crystals that impede tight packing in the material structure and are readily soluble; C-S-H has a denser amorphous structure and is far less soluble. It is the C-S-H, therefore, that gives cement its binding strength, while high CH content promotes void formation and a more extensive pore network. CH buffers the pore solution at high pH through dissociation of OH^- ions, and can also react with pozzolanic SCM (see below) to form more C-S-H and other low-solubility hydrates.

The water-cement ratio is a key factor in determining the properties of the final product: a low value (around 0.4) results in high strength and low permeability, whereas a higher ratio (above 0.6) can lead to weak and porous concrete, as excess unbound water eventually evaporates and leaves voids. The preparation of cement-based materials varies depending on the intended use. Mortar is used for binding individual bricks together, and uses fine sand as an aggregate with a relatively high water content for workability and adhesion. Concrete, on the other hand, is designed for structural strength and durability: the water-to-cement ratio is reduced and aggregate and SCM content increased with the product strength requirements. Lower-strength concrete (e.g. C10-C15[8]) is used for non-structural applications such as foundations for paving and pathways; medium-strength concrete (e.g. C20-C35) is used in general construction; high-strength concrete (e.g. C35 and above) is used in bridges and high-rise buildings.

The three major types of SCM consumed at scale are pulverised fly ash (PFA) from coal-fired power stations, silica fume from silicon furnaces, and ground granulated blast furnace slag (GGBS) from metallurgical facilities[9]. Alone or in combination with other compounds, these SCM act as binders; can enhance strength, chemical durability, and workability; and may reduce the heat of hydration as concrete sets[10]. Use of SCM also directly offsets some consumption of cement, substituting it for industrial waste which reduces the cost and calcination emissions per unit of finished concrete (Ireland Department of Enterprise, Trade, and Employment, 2024; J. V. S. Silva et al., 2024). At the same time, it should be noted that

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[8] The C# labels denote the load-bearing capacity of concrete, in megapascals (MPa, million newtons per square metre), after 28 days of setting time. C10 means the concrete is rated to support 10 MPa.

[9] GGBS is classified as 'cementitious' SCM, which, like Portland cement, develops natural binding properties upon hydration through the formation of C-S-H. PFA and silica fume (not to be confused with fumed silica) are on the other hand is classified as a 'pozzolanic' SCM, reacting with CH to form C-S-H rather than forming C-S-H directly. Because of the extra reaction step, pozzolanic SCM tends to strengthen at a slower rate than cementitious SCM.

[10] This is desirable as excessive heat release may induce cracking due to thermal stress in large structures.

changing future patterns of heavy industry and the decline of coal power in some regions will reduce the availability of some types of SCM in future.

2.1.3 Absorption of CO_2

The hydrated compounds CH and C-S-H form a hard structure relatively quickly. Finished concrete nevertheless contains pores containing excess moisture that did not react away during hydration; the pores are permeable to water molecules and to air. Carbon dioxide dissolves in and reacts with water to form carbonic acid; this in turn dissociates into hydrogen cations and bicarbonate and carbonate anions (Engelsen et al., 2005). When these anions come into contact with metal ions in the concrete pore network, the resulting chemical reactions may produce compounds like calcium carbonate – the very same compound that was originally calcinated to make the cement clinker.

The carbonation of alkaline earth metals (chiefly calcium and magnesium) is an exothermic reaction where strong chemical bonds form spontaneously at standard temperature: this means that these carbonates are relatively inert and insoluble[11]. In the context of cement, calcium is the most common metal cation and hence calcium carbonate is the mineral that precipitates out of the solution – typically in the form of amorphous calcium carbonate, vaterite, or calcite (von Greve-Dierfeld et al., 2020)[12]. The production of stable carbonates in the pores of the concrete material can be considered a durable carbon sequestration; a key corollary is that the accumulation of insoluble crystals in the pores and on the surface of the reactive minerals will impede water ingress and ion mobility, slowing down further recarbonation (Lagerblad, 2005; Rathnakumar & Garg, 2024). Figure 2.1 shows an electron micrograph of a carbonating CH paste, where deposited calcium carbonate forms a barrier to further reaction[13].

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[11] The carbonates of group-1 ‘alkali metals’ (sodium, potassium, etc.) are more soluble (IPCC, 2005).

[12] Calcite is the most stable, and other forms will gradually reconfigure into calcite (Lagerblad, 2005).

[13] The deposits in Figure 2.1 are amorphous calcium carbonate. As shown in the original source, Cizer et al. (2012), in the normal course of events these would be expected to re-dissolve and re-precipitate as calcite crystals which present a more impermeable barrier. We chose to depict the temporary amorphous phase simply because the substrate is more visible in that particular image.

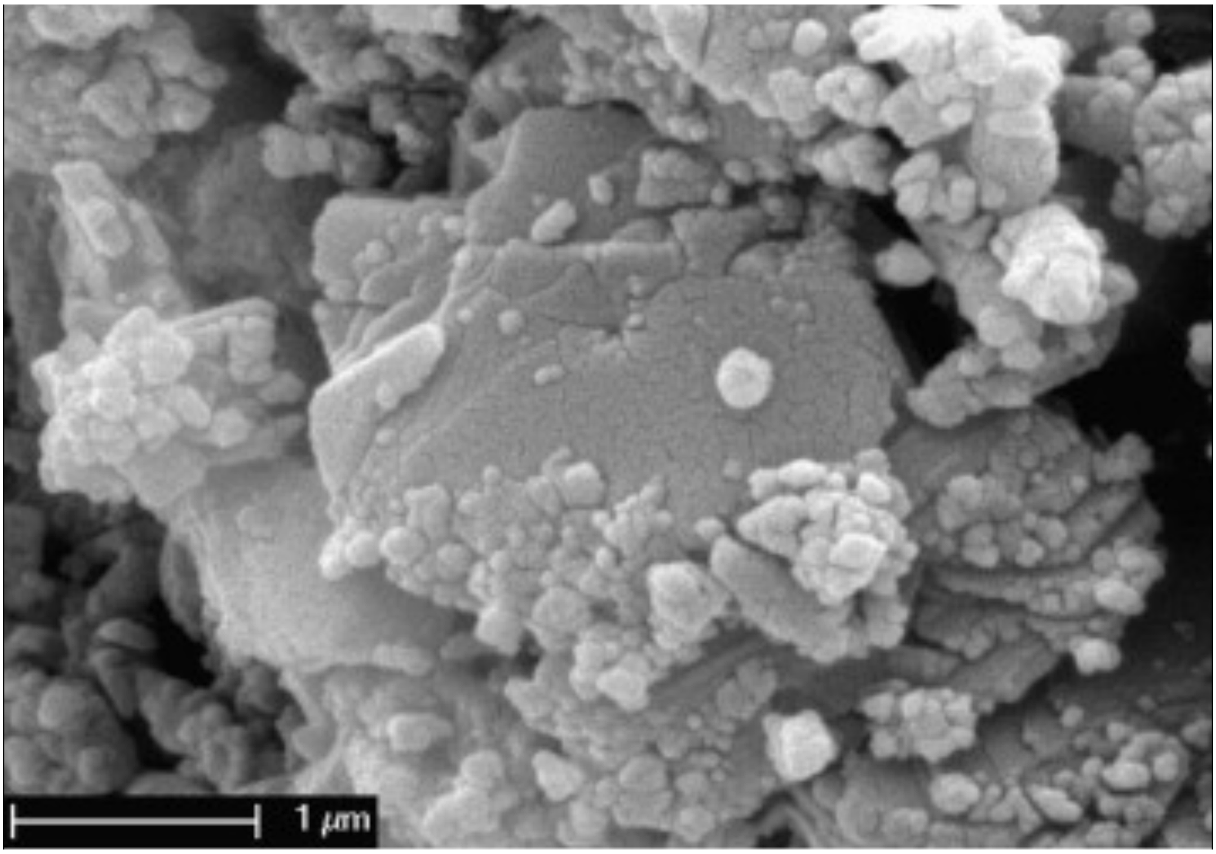

Figure 2.1 Calcium carbonate deposits on portlandite

Source: Cizer et al. (2012)

Figure 2.2 illustrates an idealised (i.e. purely thermodynamic) recarbonation pathway for a typical Portland cement mixture. 'Cement blend' on the horizontal axis indicates a blend of cement powder, which is then hydrated with 50 g of water per 100 g of cement powder to make cement paste. Recarbonation proceeds from right to left in the figure, with the pH of the mineral solution decreasing (i.e. becoming more acidic) as the dissolution of CO_2 to form bicarbonate and carbonate ions releases hydrogen ions into the water. Once the cement hydrates have all completely reacted, the indicated mass of bound CO_2 is 50 g per 100 g of cement powder – this large mass increment is consistent with stoichiometry of typical cement mixes[14]; but the degree to which it is actually realised in practice depends on kinetic barriers and the time available to allow reactions to take place.

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[14] The molecular masses of CaO and CO_2 are 56 and 44 respectively. Carbonating a single molecule of CaO to make a molecule of $CaCO_3$ would represent a mass increase of 79%; thus, an (un-hydrated) cement blend containing around 63% CaO would achieve a carbonation mass increase of 50%.

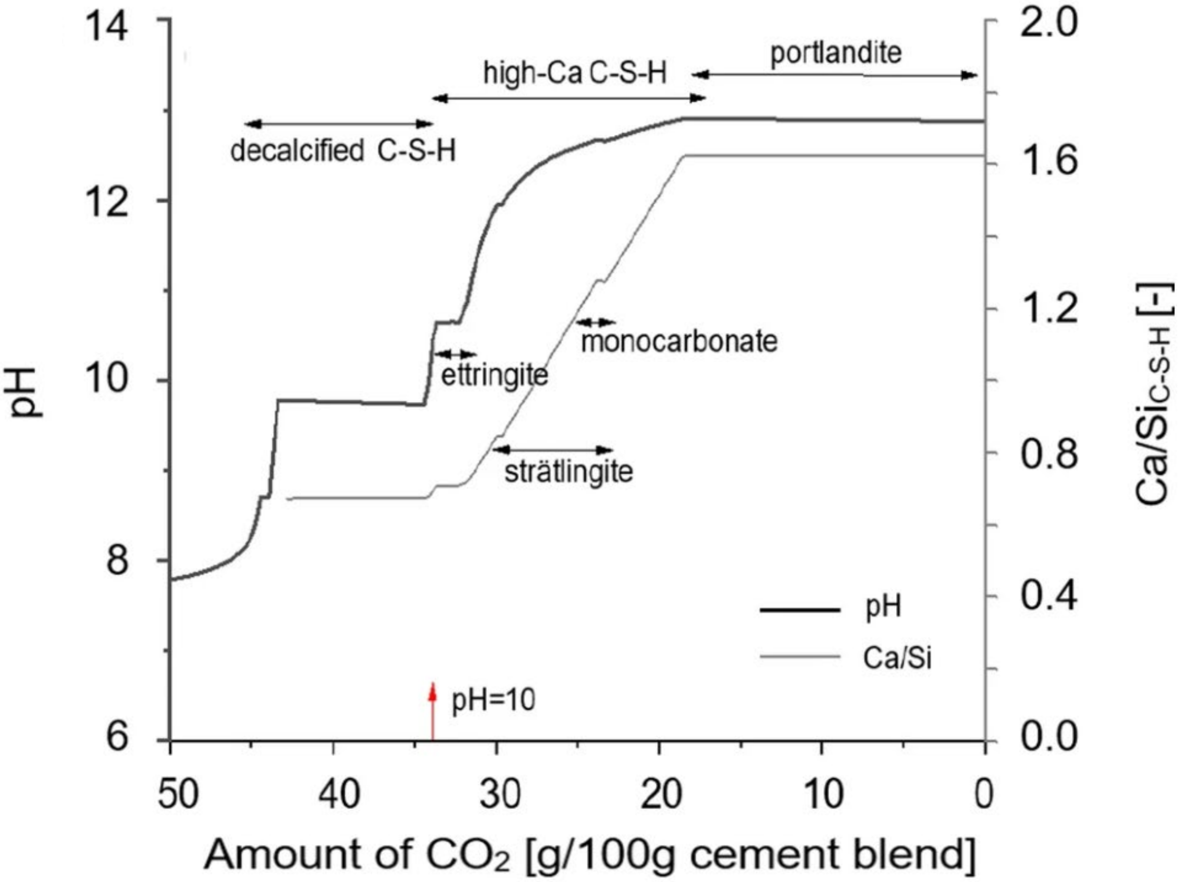

Figure 2.2 Sequence of reactions between CO_2 and minerals found in cement, showing the evolution of carbon content, pH, and the ratio of calcium and silicon in C-S-H along the reaction path

Source: von Greve-Dierfeld et al. (2020)

In general, carbonation is expected to strengthen concrete (Monkman et al., 2016; D. Zhang et al., 2017a), as the formation of calcium carbonate creates a denser microstructure[15]. As will be emphasised in Section 2.3, a key factor in the speed of the carbonation reaction is the porosity of the concrete, which is influenced by a few key factors: the cement mix and the presence of cementitious SCM[16], determines the balance between pore-forming CH and denser C-S-H (as well as other minerals); the amount of water added influences the size and frequency of voids that remain after water has evaporated during the curing phase; the size distribution of aggregate affects packing (large, homogenous grains tend to allow voids to form, while smaller grains in a variety of sizes pack more densely); and the inclusion of pozzolanic compounds like SiO_2 and Al_2O_3 gradually consumes CH and blocks up pores with precipitated C-S-H and other minerals.

Conversion of calcium hydroxide into calcium carbonate plus water neutralises hydroxide ions in the solution, making it more acidic (i.e. reducing the pH – see Figure 2.2): this can have adverse consequences for reinforced concrete used in heavy structural applications, as steel structural elements can start to corrode at a pH below 9, and this in turn causes micro-cracks

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[15] A small amount of limestone is included in some cement preparations to provide nucleation sites that hasten calcium carbonate formation.

[16] See e.g. Figure 4 of von Greve-Dierfeld et al. (2020), and Kellouche et al. (2019).

to form (Sirotti, 2025)[17]. There has been a considerable body of research aimed at impeding the re-absorption of atmospheric CO_2 to slow recarbonation (X. Wang et al., 2024). Other research has sought to achieve recarbonation through 'CO_2-curing' (Section 2.4) in a way that avoids corrosion (D. Zhang & Shao, 2016).

A complete reversal of the calcination process would see each calcium atom in the concrete binding with one carbon atom from CO_2 to make calcium carbonate. However, after a long time exposed to carbon dioxide and water, a given concrete preparation will naturally reach a maximum recarbonation level less than 100%, as not all calcium in the material will be free to enter into solution and react with carbonate. The proportion of atoms that are ultimately bound is sometimes referred to as the 'degree of carbonation' (DoC). A value of 75% is often quoted in the industry and academic literature (see, e.g. Figure 2.4 in a later section); however, this will be sensitive to the material's chemistry and its physical characteristics like porosity, and a rather wide range of DoCs may be observed in laboratory experiments and real-world samples (Galan et al., 2010a, 2010b; Gluth & Bernal, 2024). The spread of DoCs is evident in Figure 2.3.

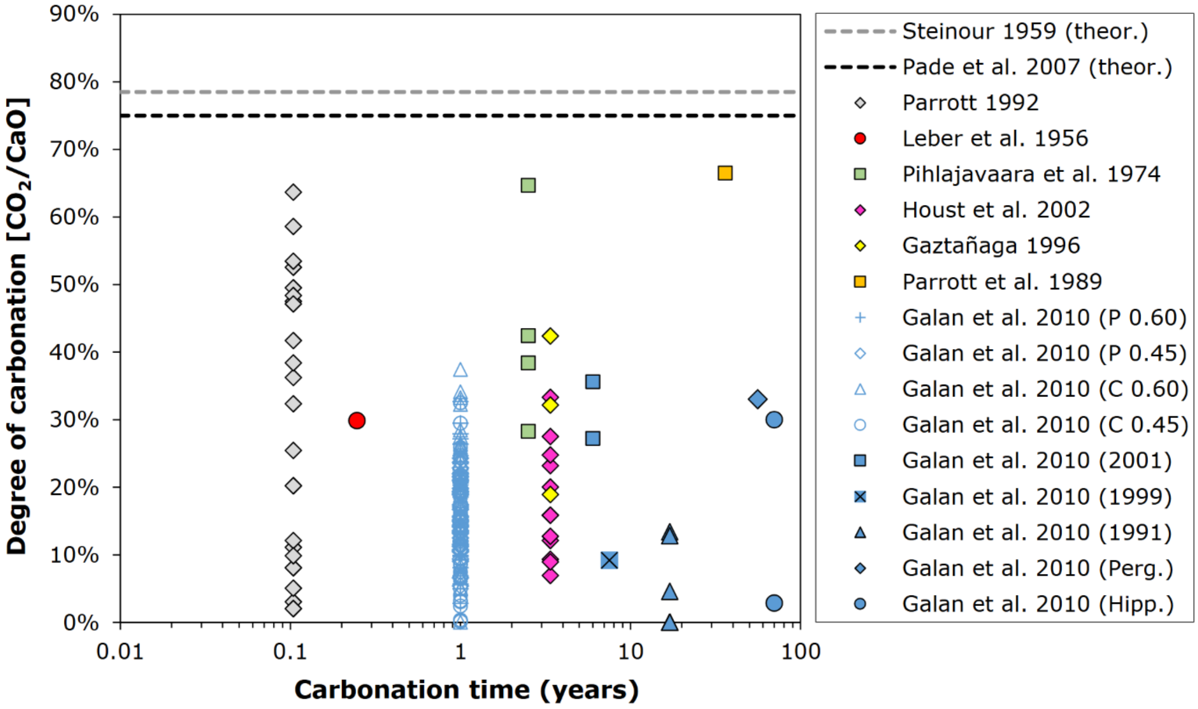

Figure 2.3 Degree of carbonation (%) in concrete as a function of sample age as reported in different studies; dashed lines indicate theoretical maximum estimates

Source: Gluth & Bernal (2024)

It could be argued that at present the evidence is insufficient for the community to come to a firm consensus on what DoC levels are achievable under different circumstances. As a corollary, any determinations of eventual CO_2 sequestration that depend on an assumed standard DoC will be inherently uncertain, and in some cases are likely to give a significant over-estimate.

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[17] This phenomenon was partly to blame for the accelerated deterioration of reinforced autoclaved aerated concrete (RAAC) that was used between 1950-90 in the UK for construction of public buildings such as schools and hospitals (Rankl & Grimes, 2024).

2.2 Other long-lived carbonating products

2.2.1 Industrial by-products

Industrial by-products with the potential to sequester carbon include metallurgical slags (e.g. from iron and steel furnaces[18]), ash from incinerators and thermal power stations, mining tailings left over after extracting valuable materials from ore (such as bauxite tailings, also called ‘red mud’), and residues from oil shale processing. Together these can be referred to as ‘industrial alkaline wastes’, indicating the high pH of the solutions that they form in the presence of water. Such solutions are capable of dissolving CO_2 and forming stable carbonate minerals (Renforth, 2019)[19], and some like steel slag are known to react quickly in humid conditions (Francsis et al., 2025).

It has been estimated that, globally, billions of tonnes of atmospheric CO_2 could be removed per year by these wastes (S.-Y. Pan et al., 2020; Renforth, 2019); though it is important to bear in mind that many of these substances are capable of absorbing CO_2 only because they have previously undergone decarbonation, e.g. under high-temperature firing. And as noted in Section 2.1.2 in the context of SCM, future production rates of these substances will be tied to developments in the heavy industries that generate them as by-products.

A detailed report for the European Lime Association studied the use of calcium carbonate and calcium oxide (lime) in a diverse range of applications – metallurgy, civil engineering, chemicals, agriculture, and heavy industry – and assessed the CO_2 binding potential of various industrial residues (Grosso et al., 2020). The report reviewed natural recarbonation rates reported in the literature under real-world conditions, and estimated the potential of accelerated recarbonation treatments to sequester CO_2. It concluded, for example, that slag from the iron industry would experience negligible natural recarbonation even after 100 years, while lime materials used in wastewater treatment would recarbonate significantly in a few decades. See Table 2.1.

Table 2.1 Recarbonation percentages for various industrial processes and products which use alkaline mineral compounds or generate them as wastes or by-products

Application / Product	Natural recarbonation (%)	Enhanced recarbonation (%)
Iron and steel industry		
Iron industry	Negligible after 100 years	7% direct route, 31% indirect route[20]
Steel industry	5% (4 months) 28% (1 year)	39-56% direct route

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[18] As a rule of thumb, around half a tonne of slag is generated per tonne of iron or steel (X. Zhang et al., 2020).

[19] While we focus here on the CO_2-uptake potential of these materials, it should be pointed out that methods under development seek to extract and recycle useful minerals from waste deposits (X. Zhang et al., 2020). Extraction of lime (CaO) from metallurgical slag, for example, would reduce the recarbonation potential of the slag; but the lime may still go on to recarbonate in its later use.

[20] Direct and indirect carbonation treatments are discussed in Section 2.4.5. Briefly, direct involves physical alterations to the material before the carbonation reactions, while indirect treatments chemically extract and purify reactive compounds for carbonation.

Construction materials		
Sand lime bricks	30% (reference time not reported)	No information identified
Light-weight lime concrete / Autoclaved aerated concrete	30% (10 years) – 60% (30 years)	No information identified
Pure air lime mortars	80-92% (after 100 years)	--
Mixed air lime mortars	20-23% (after 100 years)	--
Hemp lime	55% (after 91 days)	65%
Civil engineering		
Soil stabilisation	37% (after 34 years)	Only lab-scale
Asphalt pavements	No information identified	No information identified
Environmental protection		
Drinking water – softening process	100% instantaneous	No information identified
Wastewater treatment – biosolids	40-50% (reference time not reported)	No information identified
Sludge treatment dredging sediments	35% (after 30 years)	No information identified
Flue gas cleaning systems	32% instantaneous	59-66% (full-scale)
Acid mine drainage	Negligible	No information identified
Agriculture		
Agriculture	No conclusive outcome	No information identified
Chemical industry		
Calcium Carbide	Depends on the next use	No information identified
Non-ferrous industry		
Aluminium production	11.5% (no information about time)	11.5%
Titanium dioxide production	No information identified	10-25% direct route, 60% indirect route
Other non-ferrous metals production	No information identified	No information identified
Pulp and paper		
Precipitated calcium carbonate (PCC)	85%-93% instantaneous	No information identified

Source: Grosso et al. (2020)

The rate of natural recarbonation of industrial alkaline wastes depends on the chemical compounds they contain and the conditions under which they are stored (e.g. Lekakh et al., 2008; Z. Pan et al., 2024). In some slags, for instance, metals are bound up in silicate compounds that have relatively low solubility and hence slow reaction times. The rate of slag cooling plays an important role in determining their chemical make-up: air-cooled steel slags may form a pure MgO phase but have their CaO locked up in calcium silicates, while rapid water-cooling can produce more free CaO (Ragipani et al., 2021).

The rate of cooling also affects the granularity and porosity of the final product, and there may be little opportunity for air to penetrate finely-ground materials stored in dense heaps or wastes which have solidified from a molten state. Similarly, wastes that are brought to landfill[21] and materials which are quickly re-used in construction will have their CO_2 exposure time limited. In such cases, only the exposed outer layer will have time to recarbonate; indeed, it is possible that an initial precipitated layer of carbonate minerals will form an impenetrable crust that halts the ingress of water and CO_2, and hence impedes further recarbonation for as long as the material remains undisturbed (Francsis et al., 2025). Wastes stored in very dry environments (e.g. Wilson et al., 2014) will not have the opportunity to undergo aqueous carbonation reactions, so may persist in their decarbonated state for a long time.

2.2.2 Chemical products for use

The production of certain substances requires carbon to be chemically bound into the structure. An important example is precipitated calcium carbonate (PCC), which has a range of industrial uses including as a coating for paper, as an additive to plastic to improve moulding and physical characteristics, as a component of adhesives, and in food and pharmaceutical industries (Noor et al., 2024). In many of these applications, the carbon can be easily released as CO_2 either during use of the product or at the end of life. For example, incineration of paper or plastic containing PCC will typically reach decarbonation temperatures.

Similar observations can be made for the compound sodium carbonate (also known as 'soda ash'), used in glass-making, detergents, water treatment, and industrial chemistry. Sodium carbonate can either be produced from mined ore or synthesised via the 'Solvay process' – a reaction between sodium chloride (regular salt), limestone, and ammonia. A modification to the Solvay process that consumes carbon dioxide as an input to make the sodium carbonate has been identified both for understanding the dynamics of passive carbon sequestration in geological CCS, and as a proposal for active carbon sequestration in products (Lackner, 2002). Some but not all of the uses mentioned above would be expected to offer long-term or even permanent storage. Glass-making takes place at high temperatures which would liberate the CO_2 from the sodium carbonate. On the other hand, in water treatment, sodium carbonate is dissolved into hard water whereupon the less soluble carbonates of alkaline earth metals (like calcium and magnesium) precipitate out of the solution and can either be used or disposed of.

2.2.3 In-situ mineralisation

In-situ mineralisation is a type of geological CCS where CO_2 is pumped underground into sites that are specifically chosen for their abundance of silicates and other alkaline minerals (Matter et al., 2007; Ye et al., 2025). The CO_2 reacts to form solid carbonates in a process akin to the other mineralisation pathways. This has been identified in the literature as an energy-efficient and scalable process (Kirmani et al., 2024), albeit one that generally proceeds on a millennial time-scale (Daval, 2018). At least one methodology for voluntary carbon removal certification

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[21] Landfilling is reportedly the most common disposal method for iron and steel slags (X. Zhang et al., 2020).

has been established (Carbfix, 2022). Uncertainty over the long-term stability and fate of the sequestered carbon is still high (cf. Daval, 2018; Trias et al., 2017), and the chemical, structural, and biological factors influencing the rate of carbonate mineralisation are the subject of ongoing research (e.g. Starnoni et al., 2024; Starnoni & Sanchez-Vila, 2024).

In-situ mineralisation is already covered by the CCS Directive and therefore is eligible as a form of storage for captured CO_2 under the CRCF methodologies on DACCS/bioCCS.

2.3 General principles of CO_2 absorption

This section discusses factors affecting the rate of natural and enhanced recarbonation, including the key material and environmental factors at play. For illustrative purposes, it is sometimes convenient to use cement and concrete as examples to build intuition; but it should be understood that the considerations outlined here may also apply to other recarbonating materials identified in the previous section.

2.3.1 CO_2 penetration and binding

The speed of CO_2 penetration and binding in a material depends on certain key factors:

- Material composition. Materials with greater porosity or with networks of small fractures recarbonate faster, as CO_2 and water reach more easily into the bulk. Higher availability of water from the interior composition of the material also increases the rate of recarbonation. Some materials have a greater natural affinity for CO_2 than others; in the case of concrete, certain SCM may engender a more porous micro-structure, allowing CO_2 to reach deeper into the bulk more quickly.
- Environment. Speed of recarbonation may be affected positively or negatively by environmental factors. Water is required for the reactions of interest[22], which will be hastened by higher temperatures. Materials that are deprived of CO_2 owing to being submerged under water or surrounded by densely-packed inorganic material will carbonate slowly, while those surrounded by decaying organic matter, e.g. in soil, will carbonate faster.
- Coatings. Paint, plaster, and other coatings[23] create a barrier that can significantly slow reactant penetration.

The combination of these factors implies, for instance, that a relatively weak and water-rich cement-based mortar will recarbonate much faster than a load-bearing block of high-strength, high-density concrete at the bottom of a dam[24].

Binding of CO_2 during recarbonation can be considered permanent under normal use and disposal conditions. A common theoretical model of recarbonation in concrete is to posit an advancing 'front' of bound CO_2 in the material – see Figure 2.4. In this paper we call the distance of this front from the exposed surface of the material the 'penetration depth' and denote it with the symbol ξ (the Greek letter 'xi'). Consider a slab of decarbonated material such as concrete. For a given type of concrete, the uptake of CO_2 progresses faster when the exposed surface area is larger. Under conditions where CO_2 is advancing into the slab from

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[22] There is an optimum humidity level where there is sufficient water in the pores to allow chemical reactions to happen, but not too much as to impede the diffusion of gaseous CO_2.

[23] These are chiefly relevant to concrete and cement-containing products, though coatings may be used on industrial wastes to prevent leaching of toxic compounds, either in waste heaps or during second use (Cui et al., 2025).

[24] Cf. the results presented in Kellouche et al. (2019), that track carbonation depth over time for cements with a range of compositions.

one face only, the recarbonation process will be complete when ξ is equal to the slab's depth. If CO_2 can advance from both the top and the bottom face (e.g. a concrete roof tile exposed to the air), the recarbonation process will complete in less time (as we shall see below in Section 3.1, only a quarter of the time is required to penetrate half the distance).

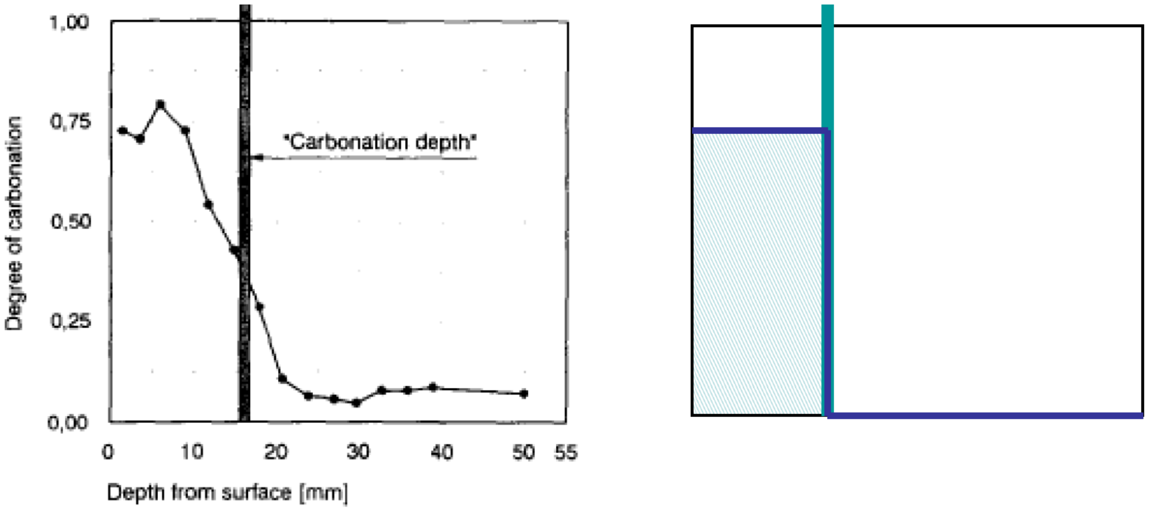

Figure 2.4 An example of the measured degree of carbonation of concrete as a function of depth into the sample (left), and the simplified 'penetration depth' model (right)

Source: Nilsson (2011)

The progress of CO_2 into the material (as depicted in Figure 2.4) may be measured by cutting a cross-section or taking a core sample and performing a pH test using a pH indicator. As mentioned in Section 2.1.3, absorption of CO_2 leads to gradual neutralisation of OH^- ions and hence acidification of the material. Because interest in recarbonation was historically motivated by the possible corrosion of steel elements, the colour indicator phenolphthalein has been used to show where the pH of the sample drops below a threshold value[25]; while this appears to be the most widely-adopted measurement technique, it provides only a rough proxy for measuring carbonate formation in the sample and it is reportedly possible to significantly over- or under-estimate the level of CO_2 binding using this method (Houst & Wittmann, 2002). Other measurement techniques have been developed (Galan et al., 2010b; Morandeau et al., 2014; J. Wang & Ma, 2023); in particular, powdered material from graded depths within a specimen can be analysed using special x-ray diffraction (Cuesta et al., 2015) or micrographic (Rathnakumar & Garg, 2024; K. Zhang et al., 2024) techniques.

It must be emphasised that, though the rate of progress of the carbonation front in concrete has historically been of interest owing to the effect on material properties, it does not in itself determine the rate of CO_2 uptake. The total mass of CO_2 bound up in the material at a given time also depends on the concentration of reactive compounds which are able to release metal ions. A greater concentration of free ions – which in the case of concrete could originate from a higher cement content – generally translates to more carbonate mineralisation and a higher absolute CO_2 sink. But the composition of the material will also affect its pore structure and the constituents of the pore solution, and how this influences the rate of CO_2 uptake is a topic of ongoing research. For example, it has been found that incorporation of SCM may facilitate or inhibit CO_2 binding (Sanjuán et al., 2020).

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[25] Phenolphthalein begins to turn from pink to colourless as the pH drops into the range 8.3-10. It is typically assumed that the colour change happens around pH 9.

2.3.2 Life stages

Industrial alkaline wastes are a diverse group of compounds produced in a variety of ways and contexts; the same is true of alkaline chemicals like PCC and soda ash, which as noted find applications in a range of industries and environments. Tracing the life sequence for this class of compounds is therefore not trivial: for the purposes of assessing permanence and baseline recarbonation, it may be necessary to treat them on a case-by-case basis.

Some key considerations have already been touched upon in Section 2.2. Bulk wastes like slag containing removed metal impurities are frequently generated at high temperatures and disposed of in piles, ponds, and pits. Following the considerations in the previous section, the level of granularity / porosity of these wastes, and the humidity / wetness of the environment, will influence the ability of CO_2 to penetrate and undergo mineralisation. For compounds synthesised purposely for industrial use, the nature of the use (e.g. whether they undergo reactions which liberate CO_2) and the ultimate fate of the products they are used in (e.g. whether they are incinerated at high temperatures) determines the baseline CO_2 emissions.

For cement, it is easier to paint the picture in broad strokes. A typical cement product has up to four life stages: primary use, demolition, secondary use, and disposal or end-of-life. Primary use is the first purpose that the cement is put to – e.g. a concrete block used in a high-rise building. The duration of the primary use stage depends on the construction type and the geographical region. New buildings may be designed to have a lifetime of 50-70 years, while civil engineering structures like bridges are designed to last longer – well over 100 years. Maintenance can extend these time-scales[26], but all structures will eventually be demolished.

Once a structure reaches the end of its useful life it is demolished and there is a span of time where the rubble will be left exposed to the air. Secondary use is when demolition waste is processed and incorporated into a new product (Kjellsen et al., 2005). High rates of recovery and re-use is reported in some developed countries (e.g., 90% in the EU and 76% in the USA), but the global average is alleged to be nearer 30% (Akhtar & Sarmah, 2018; Cho et al., 2022; T. Zhang et al., 2025). The main use of crushed recycled concrete in the UK is for road bases and piling mats (Capon & de Saulles, 2023)[27]. In the EU, secondary use varies by Member State, and is distinguished between recycling (e.g. in roads) and backfilling excavations and landscaping activities (European Environment Agency, 2020). Motivated by waste reduction and circular economy objectives, there is a growing effort to develop alternative (and higher-grade) secondary-use options beyond backfill and road bedding: primarily in recycled concrete aggregate (RCA), where conventionally mined aggregate can be replaced with demolition waste that has been screened for quality, cleaned of excess hardened cement, and ground to specification (Interreg Central Europe, 2024; Pacheco et al., 2023). Note that the slate of secondary uses observed in the EU+UK may not be representative of other parts of the world, especially where building quality codes are less stringent or less stringently enforced[28]. At the very end of its life stage, demolition waste may be abandoned or landfilled[29].

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[26] In the USA, 82-87% of concrete consumed over the previous hundred years was estimated to be still in use (Kapur et al., 2008).

[27] The National Federation of Demolition Contractors is quoted as saying that demolition concrete in the UK typically sits for two to eight weeks before it is removed, reused onsite, or crushed onsite (Capon & de Saulles, 2023).

[28] Use of recycled concrete as aggregate has been linked with accelerated degradation or reduced durability under some circumstances (Thomas & Monkman, 2022; Zhao et al., 2020).

[29] Incinerators (both for energy recovery and for disposal) reach decarbonation temperatures, meaning that any incinerated concrete waste will liberate the CO_2 that was formerly supposed to be permanently bound. However, we believe that only small volumes of concrete will reach incinerators: the fraction of demolition waste disposed of via incineration, as reported by European Environment Agency (2020), will consist chiefly of wood.

The duration of each stage in years, the physical form and dimensions of the concrete, and the environment it experiences, all impact the uptake of CO_2. Over a 50-100 year service life, a generic concrete element (excluding mortar and cement pastes) may reabsorb a non-negligible proportion of the CO_2 released during cement calcination (say 10-30% (Stripple et al., 2018; Tanzer et al., 2021)). After a building is demolished, the concrete is typically broken up on-site and potentially transported to another facility for further grinding and grading. This increases the surface area and can dramatically hasten CO_2 uptake. Andersson et al. (2019) states:

> *"After the service life of a concrete structure, it will be demolished and typically crushed into finer pieces. This will increase the specific surface area and increase the carbonation rate. A complete CO_2 uptake model must therefore calculate the CO_2 uptake in the different cement-containing products during their lifetime as well as in the end-of-life processes and when used as secondary products such as crushed concrete in a road base or as landfilling material."*

As we shall see in Section 3.2, this has important implications for the expected baseline recarbonation of concrete on timescales relevant to the CRCF. After demolition, we could expect small grains of concrete rubble to recarbonate quickly if exposed to the air. Engelsen et al. (2005) state that natural uptake of 60-80% of calcination emissions can be achieved in grains of size 1-8 mm exposed to air in 20-35 days. However, it is far from guaranteed that second-use and end-of-life concrete will be crushed small enough and allowed to recarbonate in this way (Cao et al., 2020). For instance, when recycled concrete is used as a base layer for roads, the grain size is in the centimetre range, meaning the time to complete recarbonation under normal circumstances could be a couple of decades; burying this material under a layer of asphalt restricts its exposure to CO_2 and recarbonation will slow as the available CO_2 is depleted.

Even without burial, CO_2 may be unable to penetrate into heaps of undisturbed demolition waste. Laboratory work by Knight & Miller (2024) showed CO_2 concentrations becoming depleted over time, at a rate determined by the grain size. Field observations of demolition concrete and recycled aggregate stored in piles concluded that the pile interior remained unreacted for extended periods, with only a superficial layer of recarbonation (Hou et al., 2025; Kikuchi & Kuroda, 2011). The same kinds of considerations apply to other recarbonating minerals in industrial wastes. As an example, a legacy 20 Mt slag deposit outside a steelworks in the UK was found to be less than 1% recarbonated (Mayes et al., 2018). While the explanation for this observation was multi-faceted, one important factor is the barrier to CO_2 ingress created by the crust of metal carbonate that forms on the outside on the deposit. Given the sizeable (and growing) global production of metallurgical slag, widespread replication of the UK steelworks findings would imply a significant untapped carbon sink.

2.4 Enhanced recarbonation approaches

2.4.1 Quantification

Enhanced recarbonation involves technologies and practices that accelerate CO_2 uptake above the natural baseline level. Quantifying the CO_2 sequestered depends on the pathway under consideration, but the present consensus is that model-based theoretical calculations of a material's potential DoC are unreliable (except when considering simple circumstances like fine powders) and quantification must be done experimentally. Where material is exposed to concentrated streams of CO_2 (as an alternative to geological CCS), the CO_2 fed into and out of the reactor can be monitored to estimate how much has been absorbed. As noted below, not all of the absorbed CO_2 is guaranteed to be bound into the material; more reliable measurement techniques for directly assessing the carbonate mineral content – based on samples – are under development (RILEM, 2022), but standardised protocols have yet to be adopted.

A full review of recarbonation technology is out of scope for this paper, which intends to focus on generic considerations for the crediting of recarbonation projects rather than the specific technical methods of each project. Nevertheless, the remainder of this section sketches an overview.

2.4.2 Cement pre-treatment

The European Commission (2024) Delegated Regulation that lists the construction materials that are understood to permanently bind CO_2 for the purposes of the ETS includes carbonated constituents of cement (Point (b)) and pre-cast concrete elements (Point (b)). Researchers have explored several methods of 'CO_2-enhanced mixing' and 'CO_2-curing': exposing wet concrete to a concentrated stream of CO_2 that accelerates recarbonation throughout the mixture before it has solidified[30]. In CO_2-enhanced mixing, a small quantity of CO_2 is injected into the mixer, potentially on the construction site where the concrete is to be used. CO_2-curing takes place in the centralised factories where pre-cast cement blocks are made: a pressurised CO_2 atmosphere (potentially using raw flue gas from the clinker production itself) is established in the chambers where the blocks undergo their initial curing process, before being transported to construction sites (D. Zhang et al., 2016)[31]. CO_2 not absorbed during mixing would have to be continuously re-captured and re-circulated. Critically, the CO_2 used for CO_2-enhanced mixing and CO_2 curing should be captured from existing industrial processes (or from the air), rather than being generated specifically for carbon curing or being diverted from other uses.

These two treatments have the potential improve concrete strength and other properties (Monkman et al., 2018; D. Zhang et al., 2017b), and forcing recarbonation to happen while the mixture is in a fluid state can avoid some of the shrinkage and cracking associated with slower passive recarbonation (Sirotti, 2025). However, it is important to recognise that these benefits are not guaranteed in every case: there may well be trade-offs between recarbonation and material properties, and operators will have to ensure that their chosen targets for the former do not unduly compromise the latter. Within this constraint, operators will also have to decide on the level of recarbonation that is economically justified, given the carbon price that they are able to realise and the extra time and energy required to achieve high rates of recarbonation[32].

With existing technologies, it is expected that CO_2-curing offers an order of magnitude more sequestration than CO_2-enhanced mixing per unit of concrete (Ravikumar et al., 2021; Tanzer et al., 2021); but considering the global scale of concrete production, the potential of either approach could still be appreciable. A baselining challenge will be the verification that a given recarbonation method will not counter-productively hinder natural recarbonation after the concrete has left the production facility: it has been observed in some instances that CO_2-

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[30] Note that above a certain concentration, CO_2 availability may cease to be the limiting factor in the recarbonation reaction, and it may be that only moderately concentrated CO_2 atmospheres will be needed before the process hits diminishing returns (cf. Kellouche et al., 2019).

[31] It should be noted that pre-fabrication of concrete elements will be applicable to some but not all construction projects, and that the curing process precludes the use of steel reinforcement which further limits the range of applications (Sirotti, 2025).

[32] As an indication, active recarbonation of pre-cast elements could technically reach DOC levels in excess of 80%, depending on the specific material in question; but a level around 50-60% is considered more reasonable on a cost basis.

curing may merely form an outer layer of recarbonated concrete (Liu et al., 2022) – this is not only the layer that would have recarbonated anyway, but deposition of calcium carbonate crystals in this layer may reduce porosity and hence prevent CO_2 from the air from reaching into the bulk of the material.

A net CO_2 saving could only be claimed for such a project if the total carbon removal is greater than the associated lifecycle emissions, which includes emissions from: the energy required to capture and deliver CO_2 to the curing facility; energy for the extra curing steps; and any indirect emissions identified as resulting from changes to the concrete strength. Re-analysis of experimental datasets by Ravikumar et al. (2021) concluded that net CO_2 emissions would be increased in 56 to 63 of the 99 scenarios spanned[33]. One key factor in this result was a finding that in about a third of studied datasets CO_2 curing had reduced rather than increased the compressive strength of the produced concrete, and therefore that more Portland cement would be needed to achieve the same strength. We note that the finding in Ravikumar et al. (2021) of diminished concrete strength in such a large number of cases stands at odds with the general consensus in the literature (cf. Section 2.1.3). This could warrant further investigation, as it may be possible to identify specific contexts in which compressive strength is more likely to suffer.

Under the CRCF, emissions associated with operating carbon capture and CO_2 transport would be addressed by the rules for calculating $GHG_{associated}$ in the existing draft specifications. However, emissions due to changes in product quality (which could be considered as an indirect emissions effect) would need to be explicitly added to the net emissions calculation to be considered. An alternative approach would be to impose additional eligibility requirements in cases where there is a risk that strength will be compromised, or even to exclude them from certification.

2.4.3 In-use cement recarbonation

A method for increasing ambient (i.e. non-captured-and-concentrated) carbon uptake of the product during its useful life involves modifying the cement formulation by incorporating SCM, such as fly ash or finely ground limestone powders, to increase the reactive surface area and alter the hydration chemistry (Andersson et al., 2019; Atiş, 2003; Boumaaza et al., 2021; Monkman et al., 2016). Similarly, ancillary chemicals designed to catalyse some stage of the carbonation reaction could in theory be added to cement powder.

The opportunity associated with SCM has been recognised in certain certification methodologies, but these are generally concerned with emissions reductions from displacing the use of Portland cement. See, for example, the draft protocol by Climate Action Reserve (2022), and the early Clean Development Mechanism methodologies (UNFCCC, 2012, 2014). Indeed, outright substitution of ‘hydraulic cement’ (such as Portland cement) with ‘non-hydraulic cement’ is also possible in some applications. Whereas the former requires water to set, the latter sets by absorbing CO_2. Use of these non-Portland cements is typically limited at present to non-structural precast elements where the setting/curing conditions can be controlled (Institution of Civil Engineers, 2022). Such a substitution would again be considered an emission reduction rather than a removal, and would hence fall outside the scope of the CRCF.

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[33] The range accounts for the statistical variation in their sampling of the 99 datasets.

2.4.4 Secondary use example: RCA

Recycled concrete aggregate is fine or coarse aggregate that is derived from demolition waste – essentially, using crushed and cleaned old concrete to make new concrete. As noted in Section 2.3.2, use of RCA is not standard practice in many countries owing to concerns about strength, durability, and the effect on concrete porosity at the cement-RCA interface (Pacheco et al., 2023; Villagran-Zaccardi et al., 2024). Mitigation of these mechanical and micro-structural engineering challenges is tractable, but requires the adoption of standards and establishment of oversight bodies to enforce those standards. Ongoing research seeks to enable wider use of RCA (T. Zhang et al., 2025).

The European Commission (2024) ETS Delegated Regulation lists carbonated aggregates in Point (a). Enhanced recarbonation of RCA with a concentrated CO_2 stream (Pacheco et al., 2023) shows promise in chemically stabilising RCA and reducing water-swelling/shrinkage of RCA grains with respect to the surrounding concrete (Villagran-Zaccardi et al., 2024; Xiao et al., 2022). Performance improvement has also been observed in fine aggregates subjected to similar treatment (Ouyang et al., 2024). This can be done under controlled conditions using CO_2 from a variety of sources, and the carbon absorbed by the RCA can be deemed permanently sequestered. Of course, at least the outer layer of the old concrete will have already naturally recarbonated during primary use, depending on the specification and duration of use; this will have to be taken into account when quantifying the CO_2 sequestration baseline.

Reported (gross) CO_2 mineralisation in actively recarbonated RCA currently falls in the range 5-50 $kgCO_2/t$, depending on composition. Fine cement particles which are a by-product of RCA cleaning may be separated out and reach much higher carbonation up to 90 $kgCO_2/t$, though owing to their small size the question of the natural recarbonation baseline becomes more acute. In any case, these are relatively small values, reflecting the fact that RCA production aims to optimise the composition of relatively inert material like rocks over old cement paste. Lifecycle analysis has shown that the carbon footprint benefits of using RCA vary by country, but that the cost of the extra processing steps means that potential benefits of using RCA may not be attainable without policy support for developing and rolling out the required technologies (N. Zhang et al., 2022)[34].

At present, it is likely that RCA will have to be introduced to construction practices judiciously and by degrees: so that the effect on mechanical properties can be monitored over time. There is a risk that degradation of concrete strength by over-incorporation of RCA may lead to compensatory measures which negate the greenhouse gas benefit of the RCA: as noted by Pacheco et al. (2023), “In projects with large incorporation ratio of recycled aggregates and/or related to buildings with deformability concerns, recycled aggregates may increase the carbon footprint and economic cost.”.

2.4.5 End-of-life treatments

Material at the end of its useful life may be subjected to physically and chemically harsher conditions like high temperatures and acidic solutions than primary-use material where strength and durability must be preserved. The same can be said of by-products which are destined for lower-grade secondary uses. This expands the range of treatment options that are available for sequestering CO_2.

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[34] Some research has emphasised that RCA production offers a more distributed option for carbon sequestration than geological CCS. E.g. Rosa et al. (2022) explore how RCA production could be coupled with biogas facilities to reduce dependence on CO_2 transport infrastructure.

2.4.5.1 Physical treatments[35]

A relatively straightforward way to enhance recarbonation in end-of-life concrete and industrial wastes would be to more thoroughly crush the material (e.g. Kusin & Molahid, 2024). This increases the available surface area for CO_2 to act, and, if the material is exposed to CO_2 at atmospheric or elevated concentrations under favourable moisture conditions (Engelsen et al., 2005; Pape & Rueda, 2024), uptake could be accelerated by orders of magnitude compared to uncrushed material[36]. Where such treatment is demonstrated to be additional to common practice, it may qualify for recognition as an accelerated carbon removal. However, the energy costs of extra grinding can be considerable, and must be weighed against the expected longer-term benefits of accelerated natural recarbonation. See also Section 2.6.1 about the implications for pollution.

In their full life-cycle assessment of concrete structures, Van Roijen et al. (2024) concluded that achieving a finer grain size increases the rate of gross CO_2 uptake, but incurs additional emissions due to energy use. Achieving a net benefit may also require the industry to actively prolong the time that demolition waste is left exposed to the elements[37]. We reproduce their results in Figure 2.5 – the crossing points of the CO_2 uptake curves and the dashed CO_2 emission lines show the time needed to break even. Further lifecycle assessment for different concrete grades and energy mixes would be needed to confirm the optimal demolition treatment.

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[35] Also called ‘direct’ or ‘one-step’ treatments in the literature.

[36] A study investigating the effect of grain size on speed of recarbonation found an interesting non-monotonic behaviour (Engelsen et al., 2005), indicating the presence of surface crust effects as mentioned in Section 2.2.

[37] The authors conclude that a grain size 1-10 mm would only yield a net CO_2 benefit if the exposure time were extended form the typical 3.5 months to 6 months. Crushing to 1-5 mm would not be justified even after one year.

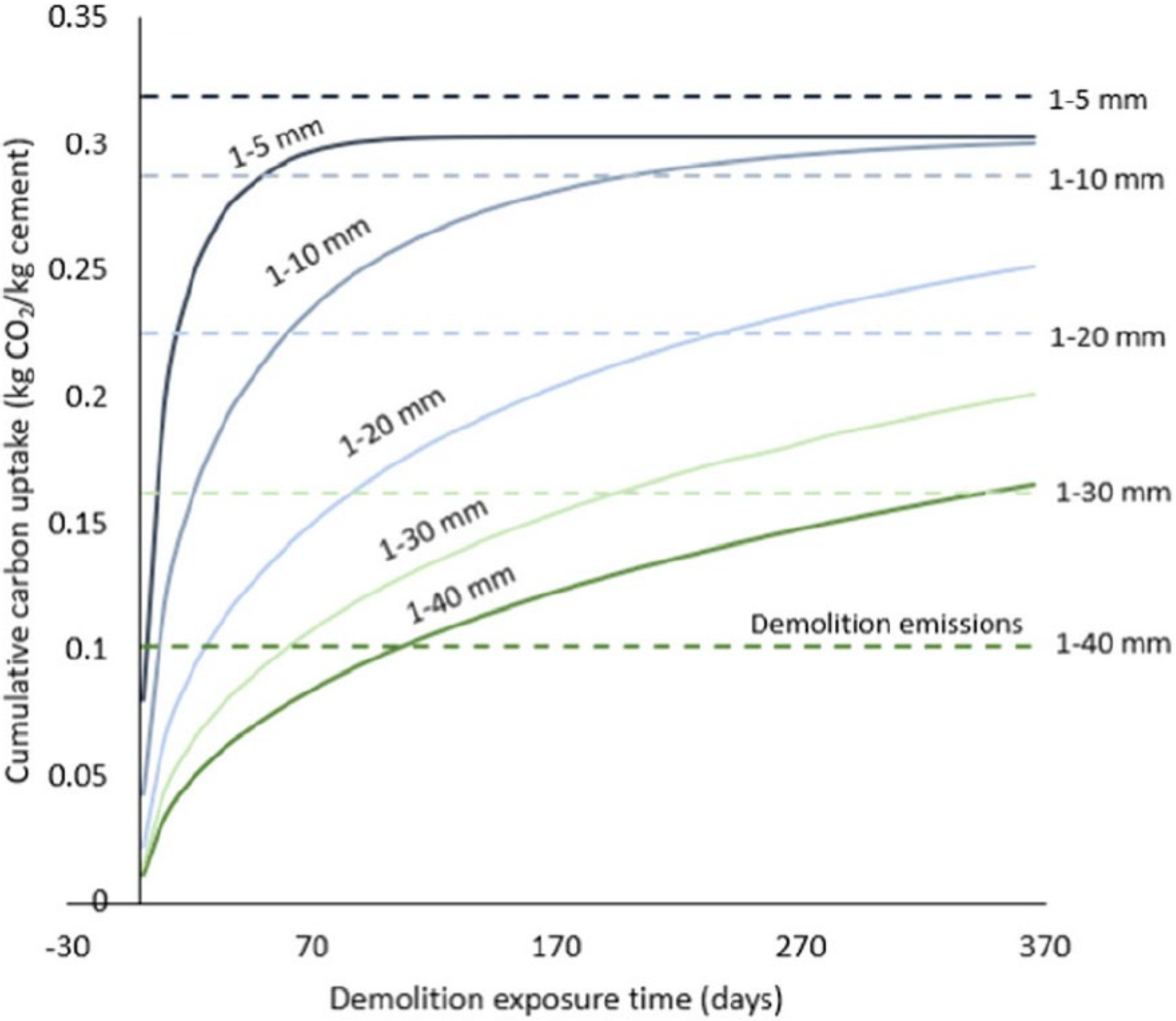

Figure 2.5 Trade-off between emissions from the crushing of demolition waste and the acceleration of natural recarbonation of crushed material

Source: Van Roijen et al. (2024)

Another example in the vein of end-of-life treatment is to move and mix heaps of material to ensure that different parts are exposed to the air and to break up mineral crusts that might form and impede water and CO_2 flow (cf. the discussion in Section 2.3.2). This kind of intervention could be relatively easy to implement as standard practice, and may already be occurring in some cases. Francsis et al. (2025) report that steel slag piles in the USA anyway undergo continual disturbance and re-exposure to the atmosphere; they argue that such material used in road-building aggregate, for instance, can be reasonably expected to thoroughly recarbonate on the time-scale of years to decades, even without active intervention. Thus, it must be understood that baseline carbonation of these by-product streams is highly practice-dependent, and may negate the potential for net carbon removal through active treatment[38]. Again, Section 2.6.1 flags the potential air- and water-quality impacts of increased disturbance.

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[38] This would disqualify the allocation of permanent carbon removal units under the CRCF, though active recarbonation's ability to bring atmospheric CO_2 uptake forward in time is itself valuable, as discussed in Section 3.2.2.

For liquid and aqueous phases such as mineral-rich tailing ponds, ultrasound can be used to agitate and mix the substrate, hastening CO_2 uptake (Bodor et al., 2013). Such activities, when properly implemented, may offer complementary benefits for the treatment of hazardous waste (Gunning et al., 2010). Other enhanced recarbonation methods and their effect on CO_2 uptake have been investigated (Chen et al., 2021; Naraharisetti et al., 2019; Santos et al., 2013), and the results of such experiments related to the underlying physical chemistry through experimental and theoretical means (Ragipani et al., 2019, 2021).

2.4.5.2 Chemical treatments[39]

Chemical extraction of metal cations – possibly following physical grinding and heating of the feedstock – can be attempted with certain solvents or acids. The carbonation reaction can then in theory be made to happen in a relatively pure solution, making the reaction easier to speed up and control (e.g. tuning the temperature, pH, and CO_2 concentration). Ragipani et al. (2021) describes a chemical process for extracting calcium and magnesium compounds, and reviews a number of studies trialling different pathways. Understanding of the reaction kinetics is still developing, and as far as the authors are aware, the economics may be hard to justify without efficiency improvements.

One advantage of the purified reaction system is that it provides easier access to potentially valuable reaction products (cf. F. Wang & Dreisinger, 2022). Precipitated calcium carbonate (PCC) was already introduced in Section 2.2 as a prototypical example of carbon storage in a non-concrete product; and an example production pathway uses thermochemical extraction of PCC from oil shale ash[40] (Ragn-Sells et al., 2024). PCC is of course stable under standard conditions; but its use in high-temperature or low-pH industrial environments, or during incineration at end-of-life, mean that it cannot be guaranteed that carbon will be sequestered long enough to be treated as permanent under the CRCF. Notably, the ETS Delegated Regulation (European Commission, 2024) does not list PCC as one of the products which permanently store carbon.

2.4.6 Silicate rocks

Naturally-occurring rocks can also be used to sequester carbon. Rocks rich in silicate minerals such as forsterite, lizardite, and wollastonite are thought to be suitable candidates that are also widely distributed and available in large quantities. Under high temperatures or specialised chemical treatments (see Section 2.4.5 immediately above), these minerals may react with CO_2 to form solid metal carbonates ($CaCO_3$ and $MgCO_3$) and silica (SiO_2)[41]. This sequestration pathway was investigated by Strunge et al. (2022), which concluded that economic viability of this approach hinges on eligibility to generate carbon credits, and the ability to use resulting carbonated material as SCM in the construction industry. The ETS Delegated Regulation (European Commission, 2024) would cover silicate materials as ‘aggregates’ (Point (a)) or as ‘masonry units’ (Point (d)).

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[39] Also called ‘indirect’ or ‘two-step’ treatments.

[40] A waste product of oil shale refining.

[41] Silicates are also the main feedstock class that has historically been considered for enhanced rock weathering (Sandford et al., 2025). In that case, the chemical process is dissolution into water rather than thermochemical treatment in a reactor, and the desired carbon sequestration is dissolved bicarbonate and carbonate ions in the ocean rather than solid carbonate minerals.

2.5 Carbon removal versus reduction

Some commentators have suggested that the natural recarbonation sink for concrete should be treated as an emission reduction to be offset against emissions from the concrete industry, as natural recarbonation is a predictable consequence of concrete production and use. There is not yet any settled treatment for this sink under the IPCC inventory system.

As noted above, enhanced recarbonation that uses a concentrated CO_2 stream captured from the atmosphere (DAC) or from a biogenic CO_2 source can be seen as an alternative form of CO_2 storage for a carbon removal activity analogous to geological carbon storage. An added advantage would be that opportunities for CO_2 storage in products could be comparatively well distributed compared to potential geological storage sites, and could lessen the need to build the CO_2 transport network infrastructure required for geological CCS.

Some stakeholders, however, would characterise enhanced carbonation as a reduction rather than a removal when it is applied to a product that is associated with significant production emissions – even if utilising non-fossil CO_2. As is noted in Section 4.1 below, the Puro standard provides an example of this philosophical approach, considering (e.g.) cement production as being within the system boundary of an activity to deliver enhanced cement recarbonation.

2.6 Sustainability considerations

Most active recarbonation approaches do not introduce fundamentally new chemistries, end uses, or disposal pathways for their feedstocks: carbon-cured concrete is still used in the same way as conventional concrete; carbonated demolition waste or steel slag must still be disposed of in the same way as their uncarbonated counterparts. Contrast this with ERW and OAE which involve new practices such as spreading basalt dust on agricultural land, and new geochemical interventions such as adding concentrated alkalinity to the coastal ocean. The sustainability impacts of active recarbonation systems are therefore likely to be relatively moderate in the sense that they are unlikely to add significantly to what happens in the existing baseline. Nevertheless, some potential adverse effects should be considered.

2.6.1 Hazardous wastes and materials

Various active recarbonation feedstocks will contain hazardous substances: primarily heavy metals, but also including basic compounds and asbestiforms. Metallurgical slags contain concentrated impurities from ores; demolition waste and basalt quarry dust may contain nickel and chromium; etc. Since these are presumably going to be produced anyway, active recarbonation projects that are co-sited with feedstock production have the advantage of existing systems for managing and disposing of the feedstock material[42].

This being said, moving hazardous feedstock around to increase carbonation rates may elevate air pollution and environmental contamination (e.g. by liberating dust and presenting new surfaces to be leached by rainwater). End-of-life treatments that involve extra crushing and grading of demolition waste could release more fine particles and toxins into the environment (cf. Bărbulescu & Hosen, 2025), as could end-of-life treatments that require material to be left outside for longer. Similarly, extra handling could expose workers to additional health hazards. These risks will be amplified if the recarbonation project requires feedstock to be loaded and transported to another location.

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[42] It is beyond the scope of this report to explore the fitness of these systems and over-arching regulation for protecting the environment and human health.

2.6.2 Material usage

In the case of recarbonated cement and aggregates for use in new constructions, the recarbonation treatment may be beneficial or detrimental to the strength and durability of the concrete. Treatments that risk weakening steel reinforcements, or requiring additional cement mix to achieve the same performance as a conventional concrete, should be avoided or could be penalised through the life-cycle emissions assessment.

There is also a hypothetical risk that the valorisation of industrial wastes will relax pressure on industrial plant operators to reduce waste generation. For instance, if a metallurgical slag is with a sufficiently high content of calcium and magnesium oxide represents an opportunity to generate carbon removal units, and the price of units was relatively high compared to the cost of limestone, then there could be a financial incentive to use extra limestone as a flux in the furnace.

2.6.3 Feedstock production and extraction

Many recarbonation pathways avoid altering the physical character of the feedstock or diverting it from other uses. For example, recarbonated aggregate can still be used in concrete production, and recarbonated demolition waste can still be used as infill. However, there may be instances where feedstock is diverted: for example, rock dust that’s a natural by-product of grinding and grading may ordinarily be used to pack and stabilise disused parts of the quarry.

The indirect methods of active recarbonation mentioned in Section 2.4.5.2 involve the use of solvents and acids that would have to be properly managed and disposed of.

3 Quantifying natural recarbonation

In this chapter, we focus on natural rather than enhanced recarbonation. This serves to illustrate some of the underlying chemistry, while establishing the key considerations for establishing baseline CO_2 removals. We note that given the relative novelty of enhanced recarbonation, it tends to be studied by the companies engaged in developing the relevant solutions and detailed results are not always available in the scientific literature.

3.1 Recarbonation models

The uptake of CO_2 by a given type of material subjected to a given set of environmental conditions is determined (approximately) by the capacity of the material to bind CO_2, and by the time-dependent penetration depth of CO_2 into the material $\xi(t)$. For a given sample of material, after ξ exceeds the sample dimensions, the recarbonation process can be assumed to be nearing completion. The sample will then have a much reduced capacity for absorbing further CO_2 and the time-dependent models examined here will no longer apply.

In the academic literature, determination of $\xi(t)$ may follow theoretical models based on physical principles, experimental investigation of samples of material, or a combination of both. Many models of CO_2 penetration into mineral-rich composites can be found, but the preponderance concern cement-based materials like concrete – often with the underlying motivation of studying and preventing the adverse effects of recarbonation on steel reinforcements (X. Wang et al., 2024). Models which are closer to first principles and have not been tuned for a specific application may be adaptable to materials beyond concrete.

Experimental research into CO_2 penetration falls into two categories: (i) study of material samples prepared in the lab, which allows researchers to precisely control the material composition and environmental conditions, potentially accelerating CO_2 uptake by enriching the atmosphere in which the sample is stored; and (ii) study of samples taken from demolition waste (in the case of concrete) or industrial waste deposits, which has the advantage of determining recarbonation in real-world applications (cf. Kikuchi & Kuroda, 2011).

Comparison of the results of approaches (i) and (ii) have shown that care must be taken when extrapolating from the laboratory to real-world results (Bernal et al., 2012; Forsdyke & Lees, 2022; Sanjuán et al., 2003; Yan et al., 2018). Taking concrete for example, conditions of elevated CO_2 levels will increase the concentration of carbonate ions found in the pore solution, but will not engender a corresponding increase in the concentration of calcium ions released from the concrete. This kind of accelerated recarbonation experiment, intent on understanding recarbonation over much longer timescales, thus accelerates one side of the natural process but not the other. Moreover, when the CO_2 concentration is kept high, then the carbonate ion concentration in the pore solution will be high, and each calcium ion that enters the solution and begins to diffuse will encounter a carbonate ion relatively quickly. Calcium carbonate will then precipitate out of solution deeper in the cement structure (i.e. close to the calcium release point), rather than in the pore space (i.e. after floating around for a while). Layers of calcium carbonate crystals may impede the release of calcium ions into solution, or may obstruct gas and liquid diffusion in the pores in a qualitatively different way to recarbonation under natural conditions.

3.1.1 Concrete-specific models

Early experimental studies of concrete going back to the 1980s found that water content and humidity were important factors affecting the speed of CO_2 penetration (Boumaaza, 2020): a conclusion that holds for a range of concrete types (e.g. Galan et al., 2010b; Jung et al., 2010; Leemann & Moro, 2016). It was concluded that the penetration depth in concrete is well described as varying in proportion to the square-root of time, $\xi(t) = k\sqrt{t}$, with proportionality factor k depending on the ambient concentration of CO_2, the diffusivity of CO_2 in the material, and the chemical composition and physical structure of the material (e.g. pore size). This means that if the penetration depth for a given sample after 10 years is 1 cm, then all else being equal, after 20 years the depth will be around 1.4 cm, and after 100 years the depth will be around 3.2 cm. Slowing penetration means that the majority of natural recarbonation activity happens early on. For undamaged structures, an appropriate approximation may be to neglect recarbonation after the ~100-year mark (Lagerblad, 2005).

Taking inspiration from experimental studies, Papadakis et al. (1991b, 1991a) presented a theoretical derivation of a formula for $\xi(t)$ in concrete which reproduced the evolution proportional to $\sqrt{t}$ – this scaling may be familiar from the general theory of diffusive processes. The derivation furthermore gave a determination of the proportionality constant k in terms of factors mentioned above for the particular kind of concrete considered. Various techniques have been developed over the years to pin down values for the proportionality factor k in concrete of different grades and with different compositions, for instance through research efforts to measure the diffusivity of CO_2 (Namoulniara et al., 2016).

Limitations of this model are discussed in Boumaaza (2020). Subsequent refinements to the Papadakis et al. (1991b, 1991a) derivation have sought to expand the domain of applicability to other kinds of material like the SCM silica fume and fly ash (e.g. Behfarnia & Rostami, 2017; Papadakis, 2000) and to different regimes of environmental conditions (e.g. K. Zhang & Xiao, 2018; Nilsson, 2011)[43]. von Greve-Dierfeld et al. (2020) discuss modifications to the proportionality constant to account for structural evolution of the pore network (e.g. arising from calcification and hence blockage as the cement carbonates and/or cracking due to drying and shrinkage (cf. Johannesson & Utgenannt, 2001)). Some researchers have sought to optimise the fit of theoretical models to real-world data (Possan et al., 2016; R. V. Silva et al., 2016). A review of selected models is presented in X. Wang et al. (2024), and a comparison with experimental data in Carević et al. (2019). This is still an active area of research, as the development of new concrete formulations can significantly alter carbonation characteristics (Carević et al., 2019; J. Wang & Ma, 2023; S. Wang et al., 2024).

For illustrative purposes, Table 3.1 presents the effect of key parameters on the carbonation speed according to one specific model (K. Zhang & Xiao, 2018); divergences from these relationships may of course be observed depending on the particular material, treatment, and other circumstances under consideration. As we shall discuss in Section 3.2.2, for practical calculations researchers often rely on a standard table of k values derived from Lagerblad (2005).

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[43] It is surprising that theoretical models based on relatively simple mass-transport arguments and without detailed consideration of the physical microstructure of concrete (e.g. pore distribution) and the chemical are able to effectively reproduce the experimentally-observed behaviour.

Table 3.1 Factors affecting carbonation, and their relationship to the one-dimensional speed of CO_2 penetration (in mm/s) according to one selected model

Category	Factor	Unit	Symbol	Effect on carbonation speed	Model relationship
Material properties	**Concrete water content**	%	W	Increase	$\sim W^{1/2}$
	Concrete cement content	%	C	Decrease	$\sim 1/C^{1/2}$
	Compressive strength	MPa	S	Decrease	$\sim 1/S^{3/2}$
Environmental conditions	**Relative humidity**	%	RH	Increase / decrease[44]	$\sim RH^{3/2}(1-RH)$
	Ambient CO_2 concentration	ppm	φ_0	Increase	$\sim \varphi_0$
	Temperature	°C	T	Increase	$\sim T^{1/4}$

Note: The modelled relationship column follows K. Zhang & Xiao (2018), and is indicative rather than definitive[45]*. The penetration depth in this model is proportional to* $\sqrt{t}$.

The time evolution of the penetration depth may also be expected to depart from the general $\sqrt{t}$ behaviour under some circumstances (Boumaaza, 2020; Carević et al., 2019). This is especially observed in certain regimes of humidity, and is important for estimating the real-world recarbonation rates. Various other factors that influence recarbonation of concrete in-use have been explored: for instance Nilsson (2011) assessed how coatings which separate concrete from the air (e.g. like paint or plaster) can slow recarbonation.

3.1.2 Non-concrete models

Natural recarbonation of materials such as alkaline industrial wastes will follow many of the same general principles as concrete. However the low practical and economic utility of understanding the physical chemistry of e.g. recarbonating slag deposits appears to have limited the investment of research resources, and hence the empirical and phenomenological understanding of specific carbonation dynamics for these materials.

Nevertheless, experimental laboratory and in-situ investigations of a range of such materials have been undertaken (Chen et al., 2021; Z. Pan et al., 2024; Ragipani et al., 2021; Santos et al., 2013) and some theoretical reaction models proposed (Gopinath & Mehra, 2016; Lekakh et al., 2008; S.-Y. Pan et al., 2018; Ragipani et al., 2019).

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[44] The value of RH that maximises the carbonation speed is exactly 3/5=60% according to the K. Zhang & Xiao (2018) model. Departure from this value in either direction will reduce the predicted speed of recarbonation. Cf. the dependence reported in Kellouche et al. (2019).

[45] As an example of the domain of applicability of this model, penetration depth is given as proportional to $T^{1/4}$. This reflects an approximation for the effect of temperature on reaction rates. But at high temperatures the solubility of CO_2 in water diminishes, reducing the speed of the recarbonation front.

3.2 CO_2 storage in built structures

3.2.1 Carbon uptake over life stages

The remainder of this chapter will focus on CO_2 uptake by concrete structures. Researchers have scaled up the theoretical and empirical findings from the previous section to apply to built structures, and thence to the national and global building stock. These analyses may integrate several models of recarbonation behaviour in order to represent the diversity of materials used in a given structure. The factors that must be considered include:

- The quantity of each type of mineral product (including concrete of different strength classes, the proportion of cement used as mortar in the construction, and the use of pre-cast versus cast-on-site building elements);
- The standard compositions of each product (i.e. the region-specific codes for the cement and aggregate compositions for different products);
- The size of the building components (e.g. large concrete blocks versus tiles);
- The use of surface coatings (e.g. paint and plaster);
- The longevity of structures (i.e. the likely lifetime before they are demolished);
- Typical second uses and end-of-life disposal practices.

The first four points are fairly self-explanatory given the review of penetration depth models in Section 3.1. A derivation of how various factors can be treated mathematically is given in Nilsson (2011).

It is worth addressing the last point directly. In Section 2.3.2 it was pointed out that after a structure is demolished and its construction materials broken up into smaller pieces for transport away from the site, its recarbonation rate will change. Consider, for instance, large concrete blocks that are crushed to make aggregate for road foundations: the significant increase in surface area will accelerate recarbonation, while subsequent burial underground will likely hinder recarbonation due to the impermeable surface restricting CO_2 ingress. Conversely, the mortar used to hold bricks or masonry together will likely be fully recarbonated and crushing at end of life will make little difference to the CO_2 balance.

Taking the post-demolition fate of concrete into consideration when calculating carbon footprints has not always been standard practice, as a report from the Swedish Cement and Concrete Research Institute laments (Lagerblad, 2005):

> *"The existing models for calculating carbonation do not take into account that the concrete is crushed and recycled after use. Consequently, the contribution of the cement and concrete industry to net CO_2 emissions is strongly overestimated."*

The report adopts the framing of end-of-life recarbonation as a form of emission reduction, seeing it as an offset against the original decarbonation emissions.

More recent studies frequently include post-demolition CO_2 absorption. For illustration, Figure 3.1 shows the results of a model that includes end-of-life demolition for a few grades of concrete (Possan et al., 2016)[46]. A considerable acceleration of recarbonation is evident upon demolition. Strong concretes recarbonate slower than weaker grades, but they have a higher maximum carbon content because of their higher cement content. In Figure 3.1, the two lower-strength concretes are seen to reach their maximum degrees of carbonation within 100 years

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[46] This paper treated post-demolition concrete as small cubes of side 3 cm exposed to the air: likely a favourable assumption compared to real-world practices.

(pink markers); the stronger preparation on the other hand may continue to recarbonate for a long time after this.

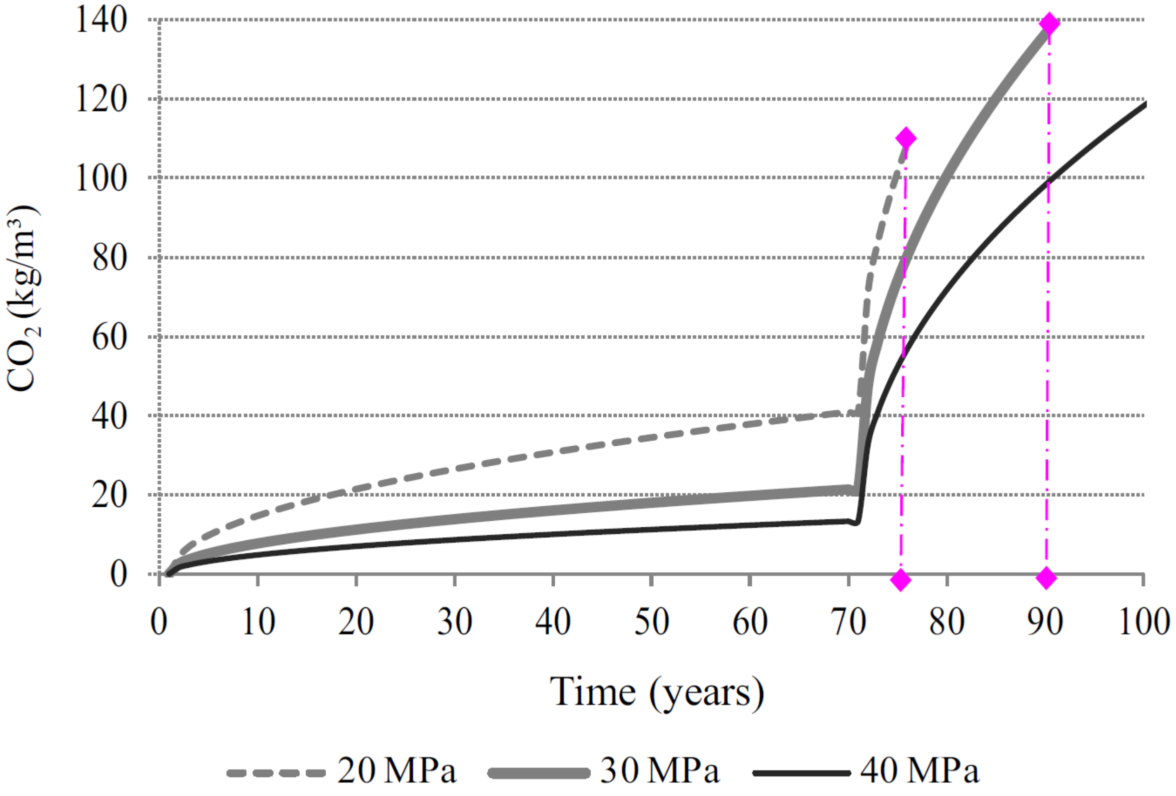

Figure 3.1 Modelled evolution of CO_2 uptake over time in concrete during the structure lifetime (0-70 years) and post-demolition (70-100 years) for three concrete grades

Note: The small apparent decrease in CO_2 content between years 70 and 71 appears to be a smoothing artefact from the authors' graphing program.

Source: Possan et al. (2016)

The implications are that a significant amount of CO_2 could indeed be naturally reabsorbed by concrete over its entire lifetime. As will be seen, this is sometimes quoted as a percentage of production emissions – calcination and fuel combustion – and sometimes as a percentage of calcination emissions only; care must be taken when interpreting results as the latter gives apparently much higher numbers. Nilsson (2011) reports:

> "*In countries with the most favourable recycling practice it is realistic to assume that 86% of the concrete is carbonated after 100 years, taking up approximately 57% of the CO_2 emitted during the calcining process [including both calcination and fuel combustion emissions]. Examples of impact of CO_2 uptake in life cycle screenings show that 70-80% of the potential CO_2 uptake has been absorbed within 100 years lifetime after demolition and crushing.*"

Other assessments have been more moderate. Van Roijen et al. (2024) consider concrete from a building that is demolished after 64 years with the rubble turned to a secondary use (buried in a roadbed): for this example, about 44% of the emissions from production (including calcination and process energy) and demolition (for crushing waste) are compensated over

100 years by recarbonation[47]. The break-down is shown in Table 3.2. Institution of Civil Engineers (2022) on the other hand concluded that an offset of 10-20% of cement calcination-only emissions over 100 years was appropriate.

Table 3.2 Indicative concrete lifecycle emissions for a building

Lifecycle stage	**Time elapsed (years)**	**Emissions source (+) or sink (-) ($kgCO_2$/kg cement)**	**Fraction of production emissions (%)**
Calcination (production)	--	+0.387	51%
Energy (production)	--	+0.367	49%
Primary use (building)	64	-0.049	-6%
Energy (demolition)	--	+0.100	13%
Rubble (demolition)	0.4	-0.116	-15%
Secondary use (road)	35	-0.166	-22%
Total	99	-0.330	-44%

Source: Van Roijen et al. (2024)

As will be seen Section 3.3 below, studies evaluating the CO_2 stored in concrete at national or global level have similarly spanned a range of recarbonation potentials.

3.2.2 Standard recarbonation rates

Estimating CO_2 uptake by concrete depends on assumed recarbonation rates (introduced in Section 3.1.1 as k). There appears to be a widespread reliance on a set of values first used in Lagerblad (2005). These are reproduced in Table 3.3, and show that k is assumed to depend on concrete strength and generic exposure conditions. Lagerblad (2005) also proposed corrections to these values depending on surface cover and the inclusion of SCM; these have since been expanded and complemented with factors that account for ambient CO_2 concentrations in different environments (e.g. levels on a busy road may be assumed to be four times those in rural areas) – see Van Roijen et al. (2024) for a collection of these factors.

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[47] The authors emphasise that these numbers are indicative, with significant sensitivity to environmental exposure and the use of coatings. As an example, concrete with an outdoor coating in a seaside environment is calculated to absorb 0.15 $kgCO_2$/kg of cement over 100 years (including demolition and secondary use), while moderate humidity and high CO_2 concentrations indoors more than doubles this to 0.34 $kgCO_2$/kg.

Table 3.3 Commonly adopted standard carbonation rates (k), in units of mm/(year)$^{1/2}$, for different concrete strengths and exposure conditions

Exposure condition	Compressive Strength (MPa)[48]			
	<15	15-20	25-35	>35
Exposed	5	2.5	1.5	1
Sheltered	10	6	4	2.5
Indoors	15	9	6	3.5
Wet	2	1	0.75	0.5
Buried	3	1.5	1	0.75

Source: Lagerblad (2005)

Corrections notwithstanding, Gluth & Bernal (2024) question the adequacy of any of these values to represent the diversity of recarbonation contexts. At the time they were introduced they constituted useful indicative estimates based on a typical Nordic climate (including patterns of indoor heating): as Lagerblad (2005) states “This is a first estimation and the values may have to be corrected when more data appear”. We are not aware of any effort for systematic verification, and owing to this Gluth & Bernal (2024) argues that the numbers lack a solid empirical basis. We understand that this applies not only to the original recarbonation rates from Lagerblad (2005), but also to subsequent corrections that have been proposed by industry studies.

As an example, ‘buried’ conditions could encompass a large range of possibilities with regards to contact with air, and adopting a single value as representative may considerably over- or under-estimate recarbonation in a given situation, and lead to systematic bias when scaling up estimates to cover wide geographies and/or long time-frames where practices may vary. Even the well-established practice of considering compressive strength classes gives little precision according to Vollpracht et al. (2024) (see also Section 3.6 of Leemann & Moro (2016)) – unsurprising given that cement formulations and production conditions vary a lot within each class and have also evolved significantly over time[49]. Thus, standard approaches to estimating baseline recarbonation of concrete should be treated very cautiously, pending further experimental work.

3.2.3 Time lag in carbon uptake

The release of CO_2 during calcination and production of cement on one hand, and its gradual reabsorption on the other, happen on very different time scales. The implications of this are two-fold.

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[48] Shown here is the ‘characteristic’ compressive strength of the concrete, which differs from the mean strength. The mean strength indicates the load under which the concrete will fail on average, while the characteristic strength indicates the load under which only 5% of samples fail. The characteristic strength of a sample will always be lower than the mean strength. Note that Lagerblad (2005) does not specify k values for the strength class between 20 and 25 MPa.

[49] Leemann & Moro (2016) found a better correlation between k and the reactive CaO content of the cement clinker, but this too was sensitive to humidity and exposure conditions.

The first implication concerns how we frame cement's net carbon footprint. As argued by Van Roijen et al. (2024), framing natural recarbonation as a percentage offset of the cement's initial calcination or production emissions, as we have done above (and as is done implicitly on the left side of Figure 3.2) misses the importance of the temporal aspect. During the period that additional CO_2 persists in the atmosphere, it contributes to global warming. Put another way, there is clearly a difference between emitting a tonne of CO_2 today and then removing half a tonne after 100 years, versus emitting just half a tonne today. Van Roijen et al. (2024) therefore integrate the cumulative warming (i.e. radiative forcing) produced by global cement consumption between 1950 and 2050 and conclude that, while 28% of cement production emissions over this time-frame would be negated by recarbonation, the reduction in global warming impact would be rather less than this.

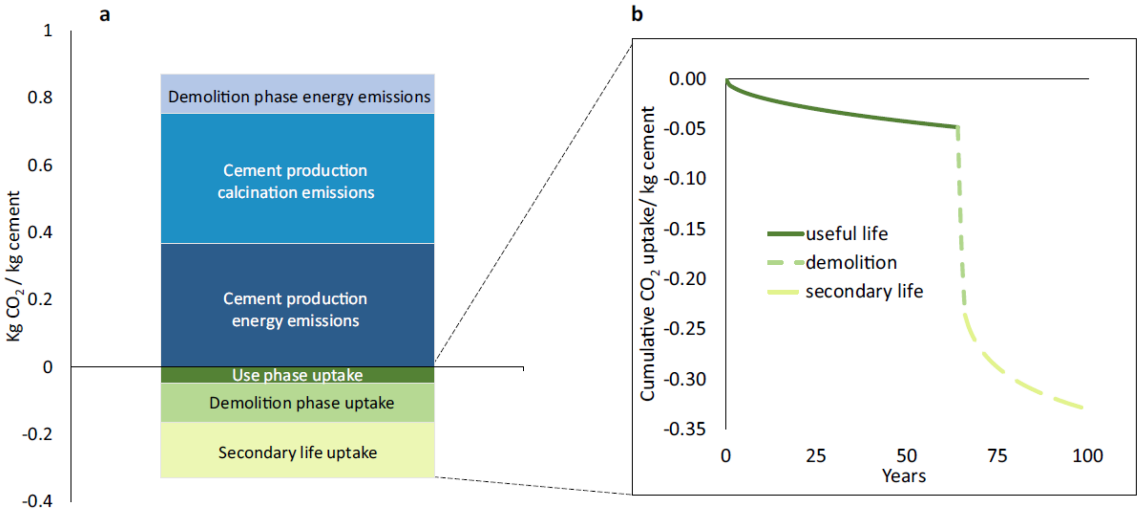

Figure 3.2 CO_2 emissions and uptake per kg of cement for illustrative life stages: (a) simple life-cycle emissions stack; (b) time-evolution of CO_2 uptake

Source: Van Roijen et al. (2024)

Note: The 'useful life' stage here assumes a typical building in an urban environment, 'demolition' involves crushing to a grain size of 1-40 mm, and the 'secondary life' stage is assumed to be burial (e.g. landfill or roadbed). During the latter stage, the carbonation rate is set much smaller than during useful life (owing to the dearth of CO_2), though as mentioned elsewhere in the text, underwater/underground k-values are subject to significant uncertainty. As is evident from the figure, in this particular analysis the higher post-demolition surface area more than compensates for the smaller chosen carbonation rate.

The same point applies to alkaline industrial wastes that have gone through a decarbonation process: the initial release of CO_2 may eventually be partially compensated, but the fraction that is reabsorbed should not be treated as simply offsetting the initial pulse.

This brings us naturally to the second implication: time is also important in comparing the global warming impacts of active versus passive recarbonation. Active recarbonation techniques that sequester CO_2 up-front (e.g. carbon curing of pre-fabricated blocks, or measures that accelerate uptake of CO_2 by slag heaps or tailings ponds) will offer climate advantages over the untreated product even if the latter eventually recarbonates to the same degree.

Only active recarbonation that goes beyond baseline CO_2 uptake rates is relevant in the CRCF context; and from the perspective of permanent removals under the CRCF the point about time lags is moot because only net sequestration above the baseline-plus-project emissions is eligible to earn credits. The fact that active recarbonation may have delivered climate benefits in the intervening period cannot be rewarded with additional permanent carbon removal units.

The question of time lags is more relevant, however if considering whether temporary carbon removals units could be issued for some of these practices.

3.3 Building stock

Estimating the carbon sink represented by a national or global building stock requires making assumptions about the mix of different types of construction material used in various building types over time, along with models of carbonation rates for these concrete types and uses. Table 3.4 presents a few examples of such analyses. All are limited in the level of detail with which the building stock is modelled – for instance, general assumptions have to be made in their classification of concrete grades used over time[50], or in the proportion of concrete that is exterior (exposed to the outside air and weather on one side), interior (exposed to inside air or surrounded by other materials), buried, and coated.

Table 3.4 Selected studies estimating CO_2 uptake by building stock

Reference & Geography	Description
Wu et al. (2024) Global	A mathematically detailed model encompassing global regions, and distinguishing concrete, mortar, and wastes, including demolition waste. From 1930 to 2023, cumulative cement CO_2 absorption was estimated at 24 $GtCO_2e$, over 50% of the period's production emissions (equivalent to about 30% of the calcination emissions). Study data available. See also similar studies (Huang et al., 2023; Xi et al., 2016).
Sanjuán et al. (2020) Spain	Uses a simple methodology with standard reabsorption factors for in-use and end-of-life concrete (see Section 3.4.2). Finds that 31 $ktCO_2$ was absorbed by cement materials produced in Spain between 2005-15 (23% of calcination emissions in 2015).
Pade & Guimaraes (2007) Nordic	Considers concrete with a 70-year service life followed by 30 years after demolition. encompasses theoretical and laboratory study of the concrete production in Denmark, Iceland, Norway and Sweden. Concludes that a significant proportion of the CO_2 emitted by calcination is reabsorbed in 100 years. See also the Nordic study (Kjellsen et al., 2005) which concluded that 57% of calcination emissions are re-absorbed in 100 years.
Andersson et al. (2013) Sweden	Approach based on a theoretical model and on field measurements. Uptake of CO_2 by all existing structures was calculated to be 300 $ktCO_2$.This represents 17% of the total production emissions (about 10% of the calcination emissions) from the production of new cement in 2011.
Van Roijen et al. (2024) Global	Modelled global CO_2 uptake between 1950 and 2050 of 46 $GtCO_2$ – equal to 28% of total production emissions over that time. Input assumptions and data provided. Follows the model developed by Xi et al. (2016) and Cao et al. (2020).
Xi et al. (2016) Global	Influential early global analysis concluded that 43% of cement calcination emissions between 1930-2013 had been re-absorbed. Based on arguably optimistic assumptions about rates of secondary use and exposure of demolition waste around the world.

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[50] Cement compositions have changed significantly over time and will continue to do so into the future (Gluth & Bernal, 2024): this represents an added layer of subtlety which is largely missing from time-integrated estimates of CO_2 uptake in the literature.

Reference & Geography	Description
Cao et al. (2020) Global	Calculates 3 $GtCO_2$ emission (58% calcination) and 0.6 $GtCO_2$ uptake per year for 2014, based on global disaggregation of concrete types, uses, and disposal routes. Projected ~30% absorption of cumulative CO_2 emissions from 2015 to 2100.

3.4 International and national methodologies

A few methodologies already exist for calculating the CO_2 sink arising from natural recarbonation of concrete at the national level. The IPCC (2006) guidelines for national greenhouse gas inventories did not include a calculation methodology for concrete recarbonation, and stated:

> *"the rate of carbonation is very slow (years to centuries) and, as a practical matter, should not be considered for good practice. This is an area for future work before inclusion into national inventories."*

The 2019 refinement to the inventory guidelines (IPCC, 2019) did not offer any update on this conclusion, and materials reviewed since then by the Emission Factor Database (EFDB) board were found interesting but not compelling enough to start work on a methodology (IPCC, 2021, 2023).

In the absence of an agreed IPCC methodology, both Sweden and the UK have put forward approaches to characterise natural recarbonation emissions. These refer to the IPCC's 'tier' taxonomy, which represents increasing levels of complexity in modelling greenhouse gas emissions. Generally, Tier 1 indicates a basic method, possibly using globally standardised emission factors provided by the IPCC, while Tier 3 involves more advanced modelling, direct measurements, and higher-resolution datasets; Tier 2 falls in-between (cf. IPCC, 2006).

3.4.1 European Committee for Standardisation (CEN)

The 2017 version of CEN's standard[51] EN 16757[52] includes a formula for calculating CO_2 uptake by concrete as a function of time during its use phase. The formula and input parameters are closely related to those in Lagerblad (2005) and Andersson et al. (2013). In units of $kgCO_2/m^2$ (Andersson et al., 2019; Capon & de Saulles, 2023):

$$\text{Uptake at surface} = \underbrace{\mathrm{k} \times \mathrm{DoC}}_{\substack{\text{application- and} \\ \text{compostion-dependent}}} \times \underbrace{\mathrm{U_{tcc}} \times \mathrm{C}}_{\text{composition-dependent}} \times \underbrace{\sqrt{\mathrm{t}}}_{\text{time-dependent}} \times 10^{-3}.$$

The factor k represents the square root of the CO_2 diffusivity in the material, which depends on the material composition, properties, and environment. In the EN standard, it is computed as the product of two sub-factors drawn from lookup tables: one sub-factor encoding the strength class and exposure condition, and another the incorporation of SCMs like coal fly ash and GGBS. The degree of carbonation, DoC in the formula, is another standard factor that expresses the fact that even after a long time, concrete exposed to natural conditions will not

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[51] A 'standard' in our context refers to a technical specification that has been developed and agreed upon for use in a country or group of countries. These specifications may define, for example, certain minimal criteria that a product must satisfy to be legally sold, or be used for guidance on the production methods of goods and services.

[52] 'Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements'.

re-absorb 100% of the CO_2 released during calcination; the EN standard gives DoC values between 40% and 85%, depending on the use case.

The maximum theoretical uptake of CO_2 by Portland cement, denoted U_{tcc}, is given a default value of 0.49 $kgCO_2$/kg-cement (cf. Footnote 14), but can be independently estimated if enough information is available. C is the cement content of the sample in units of kg/m^3 (e.g. a standard concrete blend might have a cement clinker content of 300 kg/m^3). Finally, $\sqrt{\mathrm{t}}$ expresses the time dependence of the penetration depth as seen in Section 3.1. The final factor is a unit conversion. In order to calculate the CO_2 uptake by an entire structure or group of structures, the formula is to be summed over all the relevant structural surfaces.

This formula, depending as it does on standard lookup values, is straightforward to use and is able to represent a range of use cases. Limitations of using standard k values have already been noted in Section 3.2. It is our understanding that a further shortcoming of this framework is that it treats CO_2 uptake as continuous – concrete never becomes saturated with CO_2, as would quickly be the case for a thin layer of porous, high-water-content mortar or even a pre-cast concrete roof tile. This issue is not acknowledged in some of the secondary literature which uses the standard (Andersson et al., 2019; Capon & de Saulles, 2023). Using the same variables defined above, the CO_2 content of a recarbonated material (i.e. where the penetration depth covers the whole bulk) should be $\mathrm{DoC} \times U_{\mathrm{tcc}} \times C$, in units of $kgCO_2$/m^3-concrete.

The EN 16757 methodology was updated in 2022 to include more detailed guidance for estimating CO_2 uptake after the primary use phase (for a period of 100 years). Alternatively, a standard additional CO_2 uptake of 5 $kgCO_2$/m^3-concrete may be applied post-demolition[53]: using a standard cement content factor, this translates to about 3% of calcination emissions (Stripple et al., 2018). This will be influenced by the handling and disposal measures that are adopted by demolition companies and others in the value chain. For instance, Kikuchi & Kuroda (2011) indicate an uptake of roughly 15% of calcination emissions (25 $kgCO_2$/m^3) in Japan; and using data from a global study by Xi et al. (2016), Stripple et al. (2018) calculates a weighted global average of 6% recarbonation at the end-of-life stage. Handling techniques may be improved in future to achieve significantly higher recarbonation than suggested by the conservative EN 16757 standard value (cf. the last paragraph of Section 2.3.2).

3.4.2 Swedish Environmental Research Institute (IVL)

Sweden was the first country to include cement recarbonation as a carbon removal in their UNFCCC national inventory report (NIR) in 2020. Recarbonation emissions have been reported every year since, but "due to the regulations for reporting to the UNFCCC, uptake of CO_2 for these sectors at present cannot be [included in the actual inventory calculations]." (Government of Sweden, 2023, 2024).

The calculations in the NIR follow a methodology developed by the Swedish Environmental Research Institute (IVL). IVL have developed a Tier 1 and a Tier 2 model for calculating CO_2 recarbonation in structures[54], both distinguishing between first-use and post-demolition stages. The NIR follows Tier 1 (Government of Sweden, 2023).

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[53] This assumes a 95% clinker content: the value is to be adjusted in proportion to the clinker fraction of the material.

[54] That the tier used to calculate the recarbonation CO_2 sink need not be the same as the tier used to report national CO_2 emissions from cement production. The higher-tier data requirements for the former quantity are comparatively more demanding (involving information on how the cement was used and in what form).

3.4.2.1 IVL Tier 1 methodology

The IVL Tier 1 methodology (Capon, 2021; IVL, 2021a) is intended to give a conservative estimate of concrete recarbonation that can be used in emissions inventory reporting. The Swedish Government included such a result in its 2020 inventory report to the UNFCCC (Capon & de Saulles, 2023). If the calcination emissions associated with cement used in a country in a given year are expressed in the national inventory in units of $MtCO_2$, then the $MtCO_2$ removed by recarbonation in the same year is estimated using standard factors which account for removals due to first-use concrete, mortars, second-use, and end-of-life concrete. The formula is:

$$\mathrm{CO_2\ removed} = \left(\underbrace{0.20}_{\text{first use}} + \underbrace{1.15 \times (\mathrm{MR} - 10\%)}_{\text{mortar}} + \underbrace{0.01}_{\text{second use}} + \underbrace{0.02}_{\text{end of life}}\right) \times (\text{Calcination emissions}),$$

where MR is the percentage of cement used in mortar, restricted for the purposes of the calculation to be between 10% and 30%. An Excel tool is provided on the IVL website (IVL, 2021a) to facilitate calculations.

The inclusion of second-use and end-of-life terms confirm that the formula is devised to incorporate information about past concrete usage (i.e. about structures that are demolished in the year for which CO_2 removal is being calculated). The IVL documentation states that the formula represents the annual recarbonation sink provided by the entire building stock, based on the last 100 years. The quantification of CO_2 removal is, however, proportional to cement consumption in the present year, rather than being based on a weighted sum of consumption over time. This approximation would have to be examined if the volume or type of national cement consumption has varied significantly over the 100-year period[55]. Further information is provided in an IVL report (Stripple et al., 2018).

The assumed second-use and end-of-life terms are that 1% of calcination emissions are re-absorbed in second use, and 2% in end-of-life: this is consistent with the (conservative) estimate given in the previous section.

3.4.2.2 IVL Tier 2 methodology

The IVL Tier 2 methodology dispenses with the formula quoted above for in-use concrete, and instead follows EN 16757. Future study could usefully assess and compare the accuracy of IVL's Tier 1 & 2 methodologies for first-use concrete – for instance whether the Tier 2 methodology accounts sufficiently for the use of mortar. For secondary use and end-of-life, Tier 2 resorts to using the standard Tier 1 methodology (IVL, 2021b). The IVL report (Stripple et al., 2018) notes that an alternative approach, if the annual amount of concrete taken out of service is known, is to set the CO_2 uptake in secondary-use and end-of-life stages to 10 $kgCO_2/m^3$-concrete[56].

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[55] Under this system, countries which are responsible for high historical cement- and concrete-related emissions are allowed to claim carbon reductions from their legacy building stock, which was constructed before emissions accounting was made mandatory under the UNFCCC treaty. This could be seen as a favourable windfall for past environmental damage, akin to crediting reforestation of lands which were denuded in the past.

[56] It is noted that under improved handling and disposal practices (where concrete is crushed into multiple fractions and stored with access to air for at least four months), uptake could be increased to 20 $kgCO_2/m^3$ (Stripple et al., 2018). Again, the amount of concrete taken in each year for second use or disposal would have to be known.

3.4.3 UK Department for Energy Security and Net Zero (DESNZ)

In 2023, DESNZ published a study undertaken by the Mineral Products Association titled 'UK Greenhouse Gas Inventory Improvement: Carbonation of Concrete Emissions Sink Modelling' (Capon & de Saulles, 2023). This sought to establish a model for carbon removals by concrete in the UK context; at the time of writing, this has not been adopted or implemented in UNFCCC inventory reporting. The core of the model was built upon the IVL Tier 2 methodology, and a review of UK-specific cement consumption and applications, as well as construction and demolition practices was undertaken to tune some of the model parameters.

For example, the recarbonation factor second-use and end-of-life concrete was estimated to be 21.4 $kgCO_2$/t-concrete or 39.41 $kgCO_2/m^3$-concrete – significantly higher than the conservative default values adopted by IVL. From an inventory reporting perspective, this adjustment will tend to favour UK emissions reduction compared to the original methodology. The report notes other divergences, such as the experimental data showing a much slower natural recarbonation rate for very-high-strength concrete than is suggested by the EN 16757 standard values.

4 Voluntary standards

This chapter covers voluntary schemes that have devised protocols for crediting CO_2 uptake by materials. We focus on schemes that could be used to credit enhanced recarbonation, with particular attention to how they treat the natural carbonation baseline. We also make the distinction between methodologies aimed at treatment of cement and concrete (e.g. carbonation of aggregate before it is incorporated into concrete), and those aimed at accelerating the carbonation of industrial by-products – most schemes consider only one or the other, but Gold Standard (Section 4.4) has methodologies for both.

4.1 Puro.earth

4.1.1 Methodology for cement and concrete products

The carbonated materials methodology from Puro (2022) requires net negative emissions from the entire material manufacture chain. In the case of finished cement and finished concrete (e.g. pre-cast blocks), calcination emissions would be in scope, rendering it essentially impossible for these products to qualify.

4.1.2 Methodology for industrial by-products and wastes

The Puro (2022) methodology considers mineral by-products and wastes from industry and construction to be emissions-free at the point of collection: these therefore have a far greater chance of qualifying to generate carbon dioxide removal certificates (CORCs)[57]. Carbon dioxide used for active recarbonation must be of biogenic origin or from direct capture from the ambient atmosphere.

The number of CORCs to be issued to a project is quantified based on the calculation of three emissions terms:

$$\text{Number of CORCs} = \mathrm{E}_{\text{stored}} - \mathrm{E}_{\text{production}} - \mathrm{E}_{\text{baseline}}$$

where E_{stored} is the amount of CO_2 sequestered by the project in carbonated material, $E_{\text{production}}$ is the greenhouse gas emissions (in units of tCO_2e) from project operations over the same period[58], and E_{baseline} represents the mass of CO_2 that would have been sequestered in the absence of the project activity over the course of 50 years.

The 50-year cutoff in the baseline can be interpreted as a view that, for the cases Puro consider for certification and under typical environmental conditions and treatment practices, the majority of natural carbonation is anticipated to be complete after this time[59]. Certified materials must not be exposed to conditions where release of the bound CO_2 may occur. For estimating E_{baseline}, operators will likely turn to results from the academic literature (Section 3.1) or protocols adopted by government agencies (Section 3.4). If recarbonation under the project scenario is less than double that under the baseline scenario, then the project does not qualify at all.

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[57] Our understanding of the methodology is that recarbonated RCA would qualify if sold as a standalone construction element.

[58] If the project outputs multiple co-products, the production emissions are to be allocated between them.

[59] Materials that are crushed and exposed to the air prior to disposal within this time-frame may undergo a high level of recarbonation in the baseline, in which case they would not be able to claim permanent removal credit for enhanced recarbonation.

4.2 Verra

4.2.1 Methodology for cement and concrete products

A standard developed by Verra (2024)[60] would certify concrete recarbonation projects as delivering carbon reductions or carbon removals based on the origin of the CO_2: DAC and biogenic CO_2 qualifies as removal (cf. Section 2.5), while CO_2 sources that are diverted from other uses or are created for the purpose of enhanced recarbonation are deemed ineligible. The methodology also recognises that CO_2-cured concrete may be stronger and there is hence an additional carbon reduction (not a removal) from offsetting some amount of cement needed for a given application. Certified projects may therefore generate a mix of carbon removal and carbon reduction credit.

Quantification of emissions reduction or removal follows a common formula, wherein the carbon content of any given type enhanced-recarbonation concrete is compared with the carbon content of the same type of untreated concrete. This type of baselining does not account for natural absorption of CO_2 during the product lifetime, meaning it will tend to over-credit net CO_2 absorption by recarbonation projects.

4.2.2 Methodology for industrial by-products and wastes

We are not aware of such a methodology at this time.

4.3 Isometric

4.3.1 Methodology for cement and concrete products

The Isometric (2024a) methodology does not consider pre-treatment of products, e.g. enhanced recarbonation of concrete is not covered.

4.3.2 Methodology for industrial by-products and wastes

The Isometric (2024a) methodology includes an ‘open-system ex-situ mineralisation’ protocol for materials which may absorb CO_2 from the atmosphere under certain conditions (Isometric, 2024b). Eligible feedstocks include mine tailings, steel slag, fly ash, cement kiln dust, and demolition waste.

A baseline (the ‘counterfactual’) is required for calculating the creditable carbon removal. The specification requires a detailed characterisation of the natural baseline carbonation rate, for instance through ongoing measurements on a control plot or a combination of measurements and geochemical modelling.

The methodology also credits mineralisation of CO_2 in the context of geological CCS, where CO_2 that has been pumped underground naturally reacts with minerals in rocks to form carbonates[61]. This is not relevant for the present purposes.

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[60] The methodology was developed in collaboration with Carbon Cure (CarbonCure, 2023).

[61] The maximum CO_2 uptake is determined in Isometric (2024c).

4.4 Gold Standard

4.4.1 Methodology for cement and concrete products

Gold Standard (2022) is a crediting methodology for projects which sequester carbon in demolished concrete that can be used in the construction industry as aggregate. Two pathways for accelerating the uptake of CO_2 are envisaged: (i) physical means like increasing the CO_2 concentration and/or crushing the mineralising material; (ii) chemical means where target compounds within the material are extracted using special solvents, whereupon they can rapidly react with CO_2 in solution[62]. No pathway for pre-treating concrete and other mineral-containing materials is considered.

The source of the CO_2 must be biogenic or DAC. The original methodology form 2022 did not consider a baseline natural rate of recarbonation – the credited carbon removal was simply the measured carbon absorbed minus the greenhouse gas emissions incurred due to the operation of the project. Since this would over-credit certified projects, a rule update was subsequently released (Gold Standard, 2024), requiring project operators to either demonstrate that natural carbonation was less than 5% of the project carbon removals, or apply a conservative discount factor on the estimated removals. Treated material which may release its carbon in subsequent use or during end-of-life disposal will be deemed ineligible for crediting.

4.4.2 Methodology for industrial by-products and wastes

Gold Standard (2025) applies to DAC or biogenic CO_2 durably sequestered as carbonates in mineral waste streams. As in the previous methodology, the two general approaches to increasing uptake of concentrated CO_2 can be broadly described as physical (e.g. crushing the solid material to finer grains) and chemical (mineral extraction using solvents).

To be eligible for certification, projects must satisfy additionality criteria (legal, financial, and practical). Project developers must put forward an appropriate baseline scenario for natural carbonation of the feedstock material (as well as for the CO_2 used in the carbonation reaction). The baseline is to account for the properties of the feedstock material and the expected sequence of environmental conditions that it could be expected to encounter. The time-frame to be considered for natural carbonation is to be set to “the average duration for which natural carbonation could occur” – i.e. however long the feedstock would be exposed to the atmosphere under typical conditions. This is an unusually stringent condition among the methodologies reviewed.

The gross quantity of CO_2 sequestered during the active carbonation process is calculated as the difference between the CO_2 fed into the reactor minus the CO_2 lost. The latter is not simply the CO_2 leaving the reactor: for solid feedstocks, the formula accounts for the possibility that CO_2 will occupy voids in the material bulk while in the concentrated CO_2 atmosphere, only to be released to the atmosphere when the material is removed from the pressurised reactor. For aqueous-phase reactions, no such term applies, though it is not impossible that CO_2 that has dissolved under pressure in the reactor chamber would likewise be released when exposed to the atmosphere. To mitigate the risk of over-estimating gross sequestration, the protocol includes a requirement to perform a carbon content analysis on the feedstock after treatment

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[62] Note that depending on reactor design, the precipitates can be retrieved and re-used as feedstocks in the chemicals industry – e.g. as PCC. In these cases, it should be carefully ascertained whether the bound carbon will be re-released to the atmosphere in subsequent use.

is complete; more experience would be needed to determine how reliable or conservative these kinds of tests will be.

The methodology includes provisions to reduce the risk of carbon leakage (e.g. if feedstock material is diverted from other uses) and reversal of carbon sequestration (e.g. if the carbonate minerals are subjected to high acidity or temperature in future).

4.5 C-Capsule

4.5.1 Methodology for cement and concrete products

C-Capsule (2023) identifies the use of carbon from biochar, DACCS, or BECCS in cement, concrete, or asphalt as creditable for CO_2 removal. Project operators are invited to submit their own calculation methodologies, to be assessed against C-Capsule's guidelines (C-Capsule, 2024); these stipulate that a submitted methodology "shall define a baseline scenario that accurately represents the counterfactual, i.e., what would have occurred without the implementation of the carbon removal activity. This baseline shall be justified through credible data sources, models, and evidence-based assumptions." To the best of our knowledge C-Capsule has not yet approved a specific approach for the baseline calculation.

4.5.2 Methodology for industrial by-products and wastes

In the same manner as above, C-Capsule (2023) identifies sequestration of biochar, DAC, and biogenic CO_2 through mineralisation.

5 Issues

This chapter summarises the major challenges foreseen in integrating carbon storage in products into a carbon removals certification scheme, and offers some suggestions on how to proceed.

5.1 Baseline carbon removals

5.1.1 Challenge

Materials that can be artificially carbonated will generally also be subject to some natural carbonation in normal conditions. This natural carbonation should be reflected in the $CR_{baseline}$ term in a carbon removal quantification. This situation is fundamentally different to the situation for geological CO_2 storage, for which a zero carbon removal baseline has been proposed under the CRCF.

Determining the natural carbonation over a given period may be relatively straightforward under some circumstances. At one end of the spectrum, mortar and thin concrete tiles used in buildings, fine particles like cement kiln dust, and granulated slag that's penetrable by the elements are likely to fully recarbonate on annual or decadal time-scales. If this recarbonation is included in the $CR_{baseline}$ term then no carbon removal units could be awarded for accelerated recarbonation by a project activity, as the CR_{total} and $CR_{baseline}$ terms would more or less cancel each other out[63].

At the other end of the spectrum, there are some applications in which recarbonation rates would be expected to be low during the primary use phase. High-strength concrete blocks used in long-lived engineering projects – bridges, dams, skyscrapers – would naturally recarbonate slowly and are not expected to be demolished until many decades or possibly centuries after building. Even a conservative baseline for natural recarbonation during the use phase would be significantly below the rate of recarbonation achievable by CO_2 curing.

Intermediate cases include concrete of moderate strength used in a range of sizes, applications, and geometries, and industrial wastes that are expected to carbonate only gradually. Determining the baseline carbonation rate in these cases may be complicated, owing to the various sensitivities to environmental conditions, and to grain size and shape. Key parameters include the surface-area-to-volume-ratio of the material, in combination with the availability of water and exposure to CO_2 (which are in turn affected by coatings applied to the surface). A tonne of concrete used in an external wall in the semi-arid Greek mainland may recarbonate slower than it would in damp Belgium.

Beyond the primary use, end-of-life for concrete products presents a major challenge to reliably characterising baseline carbonation. Large blocks of concrete that recarbonate only slowly during primary use may begin to recarbonate rapidly if crushed after demolition, owing to a higher surface area. The secondary use or disposal of this demolition rubble will then entail exposure to yet another set of environmental conditions – potentially with high or with low penetration of water and/or CO_2 (e.g. use of treated rubble as recycled concrete aggregate or buried in roadbeds). The natural recarbonation baseline may be much more sensitive to how long demolition rubble is left exposed before secondary use, and what secondary use is chosen, than it is to the first decades of primary use. Clearly it introduces considerable

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[63] This observation potentially affects materials listed in each of the four categories of construction materials designated in European Commission (2024) as permanently binding CO_2 in for the purpose of the ETS.

uncertainty into the baselining if secondary and end-of-life treatment has to be predicted over a century in advance.

Similar observations apply to alkaline industrial wastes. The form in which they are generated, how long they are left outside in stockpiles, the density of these stockpiles and their capacity to from mineral crusts, whether the piles are disturbed, and whether they can be put to some secondary use – all these factors will have implications for baselining.

5.1.2 Options

5.1.2.1 Single baseline values by material

Average baseline carbonation values could be estimated for a given time period for a set of eligible materials. For example, a value for average baseline carbonation rate in cement could be informed by the work undertaken by Sweden and the UK to develop estimates of their building stock's contribution to national greenhouse gas inventories. These models account for end-of-life and secondary use using simple conservative parameters. It is important to note that estimates of recarbonation that are conservative in the context of estimating and accounting for natural recarbonation (as these ones are) would not be conservative in the context of carbon removal certification: put another way, applying an intentionally low natural recarbonation estimate to active recarbonation projects would translate to a low baseline that would unduly amplify crediting. This would have to be managed.

Another limitation of this approach is that a single baseline assumption would have to reflect a potentially wide range of use cases for the given material, and would moreover have to be founded on existing estimates of carbonation rates from the literature that remain contentious even after decades of research, and that are subject to continual evolution as cement blends and preparation techniques develop. In the case of alkaline industrial wastes, even less is known about the kinetic parameters and the diversity of material management practices that would go to inform the construction of the baseline.

Thus, the single baseline approach would mean that in some contexts net carbon removals would be certified that would not actually be achieved, while in others they would be systematically understated. This would not only fail to accurately quantify carbon removals, but could fail to motivate operators to target high-impact projects, as the rigid baseline would be insensitive to these decisions. This option therefore comes with considerable drawbacks.

5.1.2.2 Detailed assessment by material characteristics and use

The other end of the spectrum from material-level defaults would be to require detailed assessments of the characteristics of each credit-generating material and the environmental conditions they will be exposed to during and after primary use. This would require a specific prediction of the material's baseline lifetime trajectory past primary use – challenging to achieve at the point of sale, as this is not data that concrete producers would routinely track. Monitoring could be required to verify the expectations (for instance checking that a concrete building containing enhanced material isn't demolished early, or that an industrial waste stockpile is disposed of in the manner predicted); but this would only give relevant visibility on a limited time-horizon; it would be difficult to impose meaningful liability on operators under a multi-century monitoring regime.

Assumed baseline recarbonation rates could in principle be verified with empirical testing of control samples – for example using 99 recarbonated blocks and one untreated block in the same project and conditions. Monitoring of that sort could lend credibility to the carbon removal claims[64] - although given that we expect a significant acceleration in recarbonation at end of life, one could debate whether regular sampling prior to end of life would be proportionate.

Again, the practicalities of long-term monitoring would need to be considered – not all building owners would want to have a certification body come and take a core sample from their building every ten years for the subsequent two centuries, and meaningful liability on longer timeframes may be difficult. Still, even if deviation from the calculated baseline was not used as the basis to specify reversals, the data gathered could inform whether default parameters and conservatism factors imposed by the methodology to mitigate over-crediting are appropriate or need to be re-evaluated (e.g. if materials are found to naturally carbonate more quickly than anticipated).

This approach implies either specifying moderately detailed baseline recarbonation functions for a range of materials and uses, or devolving to the operators and certification bodies/schemes the responsibility of preparing and validating baseline claims. It should be noted that under the CRCF if activity-specific baselines are required instead of setting a standardised baselines, this has implications for the assessment of additionality.

5.1.2.3 Restricted eligibility

In parallel to the above options, a cautious approach may begin by identifying a relatively restricted set of materials and use cases that were eligible for consideration – for example, concrete prepared above a certain threshold value of the cement-water ratio, that is formed into blocks of some minimum dimension. Allowing only a restricted subset of use cases for which baseline recarbonation can be modelled with relative confidence would reduce the uncertainty implied by using a simplified approach such as the ‘single-baseline’ option.

This could reduce the administrative burden along with the risk that ineffective projects would be certified. The obvious criticism is that the approach would exclude swaths of projects with promise to sequester $CO_{2,}$ and hinder technological innovation and development.

5.2 Temporary versus permanent carbon removals

Enhanced recarbonation has the potential to reduce concentrations of CO_2 in the atmosphere immediately. For some materials, natural recarbonation processes will ‘catch up’ over time, diminishing or eliminating the net CO_2 removal implied by the enhanced recarbonation when considered on the time-scale of permanent removal. This report is focussed on permanent carbon removal options, but we note that even if the net benefit would be much diminished or approach zero on the multi-century time-scale, especially if most natural recarbonation happens quickly following end of life, enhanced recarbonation could be considered as a form of temporary carbon removal, and may therefore be a candidate for certification for temporary units (‘long-term’ carbon storage in products).

Even if considered as a form of temporary carbon removal, many of the questions discussed in this paper remain relevant – for instance, not all use of concrete would deliver meaningfully increased carbon storage even on the decadal scale of temporary carbon removal.

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[64] If adopting the practice of verification by control samples, it would be important to avoid the case that practices different to business as usual were adopted to exaggerate the measured outcomes – for example by producing a coarser grade of by-product for the recarbonation project than would be normal, or otherwise by modifying management practices for waste stockpiles.

5.3 Pre-treatment versus end-of-life management

This paper discusses both actively enhanced recarbonation in mineral products utilising captured carbon (through treatments such as CO_2-curing of concrete) and enabling enhanced natural recarbonation at end of life (by crushing and/or aerating waste materials). The former category of projects could fit into the CRCF framework as a form of storage alongside geological storage in DACCS and bioCCS methodologies. The latter category accelerates absorption of CO_2 from the atmosphere without any role for captured CO_2, and is less reliant on new technologies and monitoring protocols than active pre-treatment (see the next section).

In cases where it is possible to deliver carbon sequestration through passive carbonation on a reasonably fast time-line, this avenue may have advantages over more active industrial methods. However, a diligent assessment of energy use and efficiency would be needed to determine the conditions under which such pathways offer credible emissions reductions. For instance, on the time-scale of centuries, the accelerated CO_2 uptake delivered by extra concrete crushing may not outweigh the emissions from the extra electricity use[65].

In the case of waste stockpile management in industrial and demolition yards, care must be taken that the spirit of the CRCF's additionality criterion continues to be satisfied in light of evolving management practices: it is possible that practices that incur little or no additional cost to the operator become the industry norm in future for whatever reason. Periodic assessment would be needed to ensure that carbon removal credits are not being generated for routine activities[66].

5.4 Measurement of enhanced CO_2 uptake

For accurate crediting of enhanced recarbonation projects, the quantity of CO_2 bound in the material may have to be measured. We can consider two scenarios. First, where enhanced recarbonation happens using concentrated captured CO_2 under controlled conditions (e.g. CO_2-curing of concrete in a dedicated facility). Second, where the enhanced recarbonation happens in the open and CO_2 is absorbed directly from the atmosphere (e.g. crushing of metallurgical slag). There may also be intermediate cases such as CO_2-enhanced mixing of concrete at the construction site which uses captured CO_2 but where some environmental conditions cannot be controlled.

In the first case where enhanced recarbonation happens in a reactor, it will be possible to measure the CO_2 consumed in the process by sampling the concentration of CO_2 in the active chamber. Due precaution should be taken however to monitor losses from out-gassing after the treatment has ended. Material exposed to high CO_2 concentrations (potentially at high pressure to increase solubility) will permanently bind carbonate ions to metal ions, but the carbon that remains in solution at elevated concentrations will fall out of chemical equilibrium when the material is exposed to standard atmospheric conditions.

In the second case where enhanced recarbonation happens in the open, it will be necessary to rely on a combination of sample measurements (possibly supported by measurements of material which have not undergone the enhanced treatment), and modelling. Rules and guidelines for what constitutes adequate monitoring will have to be established.

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[65] Though the balance will of course change over time as the grid decarbonises, underscoring the importance or reviewing and updating default parameters.

[66] Rather than awarding CRCF credits, it may be appropriate for the EU to issue guidance or regulation to maximise CO_2 uptake in waste stockpiles where low-cost and easily implementable measures are applicable.

5.5 Preservation of material properties

In the specific case of actively recarbonated concrete, it is important to account for any negative impacts that the treatment may have on strength and durability. Under some circumstances, the CO_2 sink may be offset by a deterioration in properties that must be compensated with extra cement powder.

This could be considered an indirect emission in the lifecycle analysis of the product, as it only emerges through comparison with alternative products that perform the same function[67]. A protocol would then need to be devised to ensure uniform treatment of this emission source. Alternatively, a decision could be made to require proof that active recarbonation treatments deliver a product of the same or higher performance to be eligible for crediting.

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[67] In the opposite case where the treatment is seen to improve material properties, this would constitute an emissions reduction rather than a removal, and hence would not be eligible for CRCF credits.

References

Akhtar, A., & Sarmah, A. K. (2018). Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. Journal of Cleaner Production, 186, 262–281. https://doi.org/10.1016/j.jclepro.2018.03.085

Andersson, R., Fridh, K., Stripple, H., & Häglund, M. (2013). Calculating CO2 Uptake for Existing Concrete Structures during and after Service Life. Environmental Science & Technology, 47(20), 11625–11633. https://doi.org/10.1021/es401775w

Andersson, R., Stripple, H., Gustafsson, T., & Ljungkrantz, C. (2019). Carbonation as a method to improve climate performance for cement based material. Cement and Concrete Research, 124, 105819. https://doi.org/10.1016/j.cemconres.2019.105819

Atiş, C. D. (2003). Accelerated carbonation and testing of concrete made with fly ash. Construction and Building Materials, 17(3), 147–152. https://doi.org/10.1016/S0950-0618(02)00116-2

Bărbulescu, A., & Hosen, K. (2025). Cement Industry Pollution and Its Impact on the Environment and Population Health: A Review. Toxics, 13(7), 587. https://doi.org/10.3390/toxics13070587

Behfarnia, K., & Rostami, M. (2017). An assessment on parameters affecting the carbonation of alkali-activated slag concrete. Journal of Cleaner Production, 157, 1–9. https://doi.org/10.1016/j.jclepro.2017.04.097

Bernal, S. A., Provis, J. L., Brice, D. G., Kilcullen, A., Duxson, P., & van Deventer, J. S. J. (2012). Accelerated carbonation testing of alkali-activated binders significantly underestimates service life: The role of pore solution chemistry. Cement and Concrete Research, 42(10), 1317–1326. https://doi.org/10.1016/j.cemconres.2012.07.002

Bodor, M., Santos, R., Gerven, T., & Vlad, M. (2013). Recent developments and perspectives on the treatment of industrial wastes by mineral carbonation—A review. Open Engineering, 3(4), 566–584. https://doi.org/10.2478/s13531-013-0115-8

Boumaaza, M. (2020). Experimental investigation of gas diffusivity and CO2-binding capacity of cementitious materials. https://theses.hal.science/tel-03285120/

Boumaaza, M., Linger, L., Boutillon, L., & Paul-Dauphin, B. (2021, June 16). Implementation of low carbon concrete: Allowance and constraints set by international main standards. A review. https://www.researchgate.net/publication/352441732_Implementation_of_low_carbon_concrete_allowance_and_constraints_set_by_international_main_standards_A_review

Cao, Z., Myers, R. J., Lupton, R. C., Duan, H., Sacchi, R., Zhou, N., Reed Miller, T., Cullen, J. M., Ge, Q., & Liu, G. (2020). The sponge effect and carbon emission mitigation potentials of the global cement cycle. Nature Communications, 11(1), 3777. https://doi.org/10.1038/s41467-020-17583-w

Capon, R. (2021). Guidance on Use of 'Tier 1 CO2 uptake model for concrete' Excel Workbook. Swedish Environmental Research Institute (IVL). https://www.ivl.se/download/18.5236a218179c58aa61426c/1622617515141/2021-05-28-Guidance-Recarbonation-Tier-1-Workbook-vn1.pdf

Capon, R., & de Saulles, T. (2023). UK GHG Inventory Improvement: Carbonation of Concrete Emissions Sink Modelling. DESNZ; MPA. https://uk-air.defra.gov.uk/assets/documents/reports/cat07/2307071003_UK_GHG_Inventory_Improvement_Recarbonation_Final_Report.pdf

Carbfix. (2022). Permanent and Secure Geological Storage of CO2 by In-Situ Carbon Mineralization v1.0. https://climeworks.com/uploads/documents/transport-&-geological-storage_methdology_carbfix_2022-(1).pdf

CarbonCure. (2023, August 10). Measuring Carbon Dioxide Uptake in CarbonCure's Mineralization Process. CarbonCure Technologies Inc. https://www.carboncure.com/concrete-corner/measuring-co2-uptake-in-carboncures-mineralization-process/

Carević, V., Ignjatović, I., & Dragaš, J. (2019). Model for practical carbonation depth prediction for high volume fly ash concrete and recycled aggregate concrete. Construction and Building Materials, 213, 194–208. https://doi.org/10.1016/j.conbuildmat.2019.03.267

C-Capsule. (2023). SD-02: Eligible Removal Types (Version 1.0). C-Capsule Code. https://c-capsule.com/documents/SD-02-C-Capsule-Removal-Types-and-Codes-v1.0.pdf

C-Capsule. (2024). QP-01: Methodology Approval (Version 2.0). Documents. https://c-capsule.com/documents

CCS Directive | Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the Geological Storage of Carbon Dioxide and Amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (2018). https://eur-lex.europa.eu/eli/dir/2009/31/oj/eng

Cement Sustainability Initiative. (2005). The Cement CO2 Protocol: CO2 Accounting and Reporting Standard for the Cement Industry. Cement Sustainability Initiative (CSI); WBCSD. http://www.co2-expert.com/pdf/WBCSD%20CSI%20Cement%20CO2%20protocol.pdf

Chen, Z., Cang, Z., Yang, F., Zhang, J., & Zhang, L. (2021). Carbonation of steelmaking slag presents an opportunity for carbon neutral: A review. Journal of CO2 Utilization, 54, 101738. https://doi.org/10.1016/j.jcou.2021.101738

Cho, N., El Asmar, M., & Aldaaja, M. (2022). An Analysis of the Impact of the Circular Economy Application on Construction and Demolition Waste in the United States of America. Sustainability, 14(16), Article 16. https://doi.org/10.3390/su141610034

Cizer, Ö., Van Balen, K., Elsen, J., & Van Gemert, D. (2012). Real-time investigation of reaction rate and mineral phase modifications of lime carbonation. Construction and Building Materials, 35, 741–751. https://doi.org/10.1016/j.conbuildmat.2012.04.036

Climate Action Reserve. (2022). Low-Carbon Cement (Version 1.0). https://www.climateactionreserve.org/wp-content/uploads/2023/02/Low-Carbon-Cement-Protocol-Draft_v1_Workgroup_January-2023.pdf

CRCF Regulation | Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 Establishing a Union Certification Framework for Permanent Carbon Removals, Carbon Farming and Carbon Storage in Products (2024). http://data.europa.eu/eli/reg/2024/3012/oj/eng

Cuesta, A., Álvarez-Pinazo, G., García-Maté, M., Santacruz, I., Aranda, M. A. G., Torre, Á. G. D. la, & León-Reina, L. (2015). Rietveld quantitative phase analysis with molybdenum radiation. Powder Diffraction, 30(1), 25–35. https://doi.org/10.1017/S0885715614000785

Cui, P., Zhou, X., Xiao, Y., & Wang, F. (2025). Enhanced environmental and self-healing performance of asphalt mixture using steel slag as the substrate of functional coatings. Construction and Building Materials, 489, 142427. https://doi.org/10.1016/j.conbuildmat.2025.142427

Daval, D. (2018). Carbon dioxide sequestration through silicate degradation and carbon mineralisation: Promises and uncertainties. Npj Materials Degradation, 2(1), 11. https://doi.org/10.1038/s41529-018-0035-4

Engelsen, C. J., Mehus, J., Pade, C., & Saether, D. H. (2005). Carbon dioxide uptake in demolished and crushed concrete. Norwegian Building Research Institute. https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/2418901/Prosjektrapport395.pdf?sequence=1

European Commission. (2024). Commission Delegated Regulation (EU) 2024/2620 of 30 July 2024 supplementing Directive 2003/87/EC of the European Parliament and of the Council as regards the requirements for considering that greenhouse gases have become permanently chemically bound in a product. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R2620&qid=1738916772479

European Environment Agency. (2020). Construction and demolition waste: Challenges and opportunities in a circular economy. https://www.eea.europa.eu/en/analysis/publications/construction-and-demolition-waste-challenges

European Union. (2024). Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC. Official Journal of the European Union. http://data.europa.eu/eli/dir/2003/87/2024-03-01/eng

Favier, A., De Wolf, C., Scrivener, K., & Habert, G. (2018). A sustainable future for the European Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry by 2050 [Report]. ETH Zurich. https://doi.org/10.3929/ethz-b-000301843

Forsdyke, J. C., & Lees, J. M. (2022). CARBONATION BEHAVIOUR OF CONCRETE EXPOSED TO NATURAL AND ACCELERATED CARBONATION CONDITIONS. https://doi.org/10.17863/CAM.85412

Francsis, M., Olson, H., & Maxbauer, D. (2025, September 17). Counterfactual Complexities [Substack newsletter]. Notes from Alkali Earth. https://alkaliearth.substack.com/p/counterfactual-complexities

Galan, I., Andrade, C., Mora, P., & Sanjuan, M. A. (2010a). Sequestration of CO2 by Concrete Carbonation | Erratum. Environmental Science & Technology, 44(12), 4830–4830. https://doi.org/10.1021/es101545d

Galan, I., Andrade, C., Mora, P., & Sanjuan, M. A. (2010b). Sequestration of CO2 by Concrete Carbonation. Environmental Science & Technology, 44(8), 3181–3186. https://doi.org/10.1021/es903581d

Gluth, G., & Bernal, S. (2024). RILEM TC CUC: Carbon dioxide uptake by concrete during and after service life – Opening Letter. RILEM Technical Letters, 9, 61–67. https://doi.org/10.21809/rilemtechlett.2024.208

Gold Standard. (2022). CARBON SEQUESTRATION THROUGH ACCELERATED CARBONATION OF CONCRETE AGGREGATE (Version 1.0). Methodology. https://globalgoals.goldstandard.org/standards/432_V1.0_CDR_Carbon_Sequestration_Through_Accelerated_Carbonation_of_Concrete_Aggregate.pdf

Gold Standard. (2024). Methodology for Carbon Sequestration through Accelerated Carbonation of Concrete Aggregate version 1.0. Gold Standard for the Global Goals. https://globalgoals.goldstandard.org/ru-2024-methodology-for-carbon-sequestration-through-accelerated-carbonation-of-concrete-aggregate-version-1-0/

Gold Standard. (2025). Carbon Mineralisation Using Reactive Mineral Waste. Gold Standard for the Global Goals. https://globalgoals.goldstandard.org/432-cdr-carbon-mineralisation-using-reactive-mineral-waste/

Gopinath, S., & Mehra, A. (2016). Carbon sequestration during steel production: Modelling the dynamics of aqueous carbonation of steel slag. Chemical Engineering Research and Design, 115, 173–181. https://doi.org/10.1016/j.cherd.2016.09.010

Government of Sweden. (2023). Sweden | 2023 National Inventory Document (NID). UNFCCC National Inventory Reports (NIR). https://unfccc.int/documents/627663

Government of Sweden. (2024). Sweden | 2024 National Inventory Document (NID). UNFCCC National Inventory Reports (NIR). https://unfccc.int/documents/645011

Grosso, M., Biganzoli, L., Campo, F. P., Pantini, S., & Tua, C. (2020). LITERATURE REVIEW ON THE ASSESSMENT OF THE CARBONATION POTENTIAL OF LIME IN DIFFERENT MARKETS AND BEYOND. European Lime Association. https://www.kalk.de/fileadmin/Home/Wissensportal/Pressemitteilungen/2021/EuLA_Carbonation_Report_2020_PolMI__01.pdf

Gunning, P. J., Hills, C. D., & Carey, P. J. (2010). Accelerated carbonation treatment of industrial wastes. Waste Management, 30(6), 1081–1090. https://doi.org/10.1016/j.wasman.2010.01.005

Hou, Y., Mahieux, P.-Y., Turcry, P., Lux, J., Jourdain, X., & Aït-Mokhtar, A. (2025). Stockpile of recycled aggregates: A carbon sink? Construction and Building Materials, 473, 140979. https://doi.org/10.1016/j.conbuildmat.2025.140979

Houst, Y. F., & Wittmann, F. H. (2002). Depth profiles of carbonates formed during natural carbonation. Cement and Concrete Research, 32(12), 1923–1930. https://doi.org/10.1016/S0008-8846(02)00908-0

Huang, Z., Wang, J., Bing, L., Qiu, Y., Guo, R., Yu, Y., Ma, M., Niu, L., Tong, D., Andrew, R. M., Friedlingstein, P., Canadell, J. G., Xi, F., & Liu, Z. (2023). Global carbon uptake of cement carbonation accounts 1930–2021. Earth System Science Data, 15(11), 4947–4958. https://doi.org/10.5194/essd-15-4947-2023

IEA. (2023). Cement. In Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. https://www.iea.org/reports/cement-3

IEA, OECD, & WBCSD. (2018). Technology Roadmap – Low-Carbon Transition in the Cement Industry. International Energy Agency, Organisation for Economic Cooperation and Development, World Business Council for Sustainable Development. https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

Institution of Civil Engineers. (2022). Low Carbon Concrete Routemap for Civil Engineers. https://www.ice.org.uk/media/q12jkljj/low-carbon-concrete-routemap.pdf

Interreg Central Europe. (2024). RECYCLING CONCRETE. https://www.interreg-central.eu/news/recycling-concrete/

IPCC. (2005). 7: Mineral carbonation and industrial uses of CO2. In Carbon Dioxide Capture and Storage. Cambridge University Press. https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/mineral-carbonation-and-industrial-uses-of-co2/

IPCC. (2006). Mineral Industry Emissions. In 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Vol. Volume 3: Industrial Processes and Product Use. Task Force on National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

IPCC. (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Task Force on National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

IPCC. (2021). Note on issues related to cement carbonation. The 19th Meeting of the Editorial Board of the IPCC Emission Factor Database (EFDB). https://www.ipcc-nggip.iges.or.jp/EFDB/otherdata/Note_on_Cement_Carbonation.pdf

IPCC. (2023). Other Data | Cement and Lime Production. IPCC Emission Factor Database (EFDB). https://www.ipcc-nggip.iges.or.jp/EFDB/otherdata.php

Ireland Department of Enterprise, Trade, and Employment. (2024). Reducing embodied carbon in cement and concrete through Public Procurement in Ireland. RPS, EY, RKD. https://www.gov.ie/en/publication/22268-reducing-embodied-carbon-in-cement-and-concrete-through-public-procurement-in-ireland/

Isometric. (2024a). Carbonated Material Storage and Monitoring v1.0. Isometric. https://registry.isometric.com/protocol/carbonated-material-storage/1.0

Isometric. (2024b). Open System Ex-situ Mineralization v1.0. Isometric. https://registry.isometric.com/protocol/open-system-ex-situ-mineralization/1.0

Isometric. (2024c). Rock and Mineral Feedstock Characterization v1.0. Isometric. https://registry.isometric.com/protocol/rock-and-mineral-feedstock-characterization/1.0

IVL. (2021a). Tier 1 CO2 uptake models for concrete [Text]. Swedish Environmental Research Institute. https://www.ivl.se/projekt/co2-concrete-uptake/calculation-models/tier-1-calculation-model.html

IVL. (2021b). Tier 2 CO2 uptake models for concrete [Text]. Swedish Environmental Research Institute. https://www.ivl.se/projekt/co2-concrete-uptake/calculation-models/tier-2-calculation-model.html

Johannesson, B., & Utgenannt, P. (2001). Microstructural changes caused by carbonation of cement mortar. Cement and Concrete Research, 31(6), 925–931. https://doi.org/10.1016/S0008-8846(01)00498-7

Johnson, M., Popstoyanova, Z., Malins, C., & Lonsdale, J. (2025). Review of carbon removal by ocean alkalinity enhancement. Support to the Development of Methodologies for the Certification of Industrial Carbon Removals with Permanent Storage.

Jung, S. H., Lee, M. K., Lee, S. L., & Oh, B. H. (2010). Experimental investigation on diffusion coefficient of carbon dioxide for sustainable construction materials. 2nd International Conference on Sustainable Construction Materials and Technologies, 361–370. http://www.claisse.info/2010%20papers/p31.pdf

Kapur, A., Keoleian, G., Kendall, A., & Kesler, S. E. (2008). Dynamic Modeling of In-Use Cement Stocks in the United States. Journal of Industrial Ecology, 12(4), 539–556. https://doi.org/10.1111/j.1530-9290.2008.00055.x

Kellouche, Y., Boukhatem, B., Ghrici, M., & Tagnit-Hamou, A. (2019). Exploring the major factors affecting fly-ash concrete carbonation using artificial neural network. Neural Computing and Applications, 31(2), 969–988. https://doi.org/10.1007/s00521-017-3052-2

Kikuchi, T., & Kuroda, Y. (2011). Carbon Dioxide Uptake in Demolished and Crushed Concrete. Journal of Advanced Concrete Technology, 9(1), 115–124. https://doi.org/10.3151/jact.9.115

Kirmani, F. U. D., Raza, A., Ahmad, S., Arif, M., & Mahmoud, M. (2024). A holistic overview of the in-situ and ex-situ carbon mineralization: Methods, mechanisms, and technical challenges. Science of The Total Environment, 943, 173836. https://doi.org/10.1016/j.scitotenv.2024.173836

Kjellsen, K. O., Guimaraes, M., & Nilsson, Å. (2005). The CO2 balance of concrete in a life cycle perspective. https://www.dti.dk/reports-on-co2-uptake-from-the-carbonation-of-concrete/co2-balance/18487,6

Knight, K. A., & Miller, S. A. (2024). Parameters Driving Concrete Carbonation at its End-of-Life for Direct Air Capture in Transportation Projects. https://doi.org/10.7922/G23X850N

Kusin, F. M., & Molahid, V. L. M. (2024). Mineral Carbonation of Mine Tailings for Long-Term Carbon Capture and Storage. In S. K. Das, K. R. Reddy, L. Nainegali, & S. Jain (Eds), Geoenvironmental and Geotechnical Issues of Coal Mine Overburden and Mine Tailings (pp. 109–131). Springer Nature. https://doi.org/10.1007/978-981-99-6294-5_8

Lackner, K. S. (2002). Carbonate Chemistry for Sequestering Fossil Carbon. Annual Review of Environment and Resources, 27, 193–232. https://doi.org/10.1146/annurev.energy.27.122001.083433

Lagerblad, B. (2005). Carbon dioxide uptake during concrete life cycle—State of the Art. Danish Technological Institute. https://www.dti.dk/_/media/21043%5F769417%5FTask%201%5Ffinal%20report%5FCBI%5FBjorn%20Lagerblad.pdf

Leemann, A., & Moro, F. (2016). Carbonation of concrete: The role of CO2 concentration, relative humidity and CO2 buffer capacity. Materials and Structures, 50(1), 30. https://doi.org/10.1617/s11527-016-0917-2

Lekakh, S. N., Rawlins, C. H., Robertson, D. G. C., Richards, V. L., & Peaslee, K. D. (2008). Kinetics of Aqueous Leaching and Carbonization of Steelmaking Slag. Metallurgical and Materials Transactions B, 39(1), 125–134. https://doi.org/10.1007/s11663-007-9112-8

Liu, J., Wang, Y., Li, Y., Tian, J., You, X., Mao, Y., Hu, X., & Shi, C. (2022). Carbonated concrete brick capturing carbon dioxide from cement kiln exhaust gas. Case Studies in Construction Materials, 17, e01474. https://doi.org/10.1016/j.cscm.2022.e01474

Matter, J. M., Takahashi, T., & Goldberg, D. (2007). Experimental evaluation of in situ CO2-water-rock reactions during CO2 injection in basaltic rocks: Implications for geological CO2 sequestration. Geochemistry, Geophysics, Geosystems, 8(2). https://doi.org/10.1029/2006GC001427

Mayes, W. M., Riley, A. L., Gomes, H. I., Brabham, P., Hamlyn, J., Pullin, H., & Renforth, P. (2018). Atmospheric CO2 Sequestration in Iron and Steel Slag: Consett, County Durham, United Kingdom. Environmental Science & Technology, 52(14), 7892–7900. https://doi.org/10.1021/acs.est.8b01883

Monkman, S., Kenward, P. A., Dipple, G., MacDonald, M., & Raudsepp, M. (2018). Activation of cement hydration with carbon dioxide. Journal of Sustainable Cement-Based Materials, 7(3), 160–181. https://doi.org/10.1080/21650373.2018.1443854

Monkman, S., MacDonald, M., Hooton, R. D., & Sandberg, P. (2016). Properties and durability of concrete produced using CO2 as an accelerating admixture. Cement and Concrete Composites, 74, 218–224. https://doi.org/10.1016/j.cemconcomp.2016.10.007

Morandeau, A., Thiéry, M., & Dangla, P. (2014). Investigation of the carbonation mechanism of CH and C-S-H in terms of kinetics, microstructure changes and moisture properties. Cement and Concrete Research, 56, 153–170. https://doi.org/10.1016/j.cemconres.2013.11.015

Namoulniara, K., Turcry, Ph., & Aït-Mokhtar, A. (2016). Measurement of CO2 effective diffusion coefficient of cementitious materials. European Journal of Environmental and Civil Engineering, 20(10), 1183–1196. https://doi.org/10.1080/19648189.2015.1132011

Naraharisetti, P. K., Yeo, T. Y., & Bu, J. (2019). New classification of CO2 mineralization processes and economic evaluation. Renewable and Sustainable Energy Reviews, 99, 220–233. https://doi.org/10.1016/j.rser.2018.10.008

Nilsson, L.-O. (2011). A new model for CO_2-absorption of concrete structures. CO_2-cycle in cement and concrete Part 7: Models for CO_2-absorption.: Vol. TVBM-3158. Building Materials, LTH, Lund University.

Noor, S., Rehman, A. ur, Iqbal, D. S., Iqbal, D. M., & Rehman, E. W. U. (2024). NOVEL APPLICATIONS OF PRECIPITATED CALCIUM CARBONATE IN FOOD, PHARMACEUTICAL, AND COSMETIC INDUSTRY. Journal of Population Therapeutics and Clinical Pharmacology, 31(1), 529–543. https://doi.org/10.53555/jptcp.v31i1.4039

Ouyang, X., Chen, J., Li, J., Wu, K., Ma, Y., & Fu, J. (2024). Production of sustainable lime-based brick using carbonated recycled concrete fines: Mechanical, mineralogical and microstructure properties. Construction and Building Materials, 411, 134385. https://doi.org/10.1016/j.conbuildmat.2023.134385

Pacheco, J., De Brito, J., & Lamperti Tornaghi, M. (2023). Use of recycled aggregates in concrete: Opportunities for upscaling in Europe. EU Joint Research Centre. https://doi.org/10.2760/144802

Pade, C., & Guimaraes, M. (2007). The CO2 uptake of concrete in a 100 year perspective. Cement and Concrete Research, 37(9), 1348–1356. https://doi.org/10.1016/j.cemconres.2007.06.009

Pan, S.-Y., Chen, Y.-H., Fan, L.-S., Kim, H., Gao, X., Ling, T.-C., Chiang, P.-C., Pei, S.-L., & Gu, G. (2020). CO2 mineralization and utilization by alkaline solid wastes for potential carbon reduction. Nature Sustainability, 3(5), 399–405. https://doi.org/10.1038/s41893-020-0486-9

Pan, S.-Y., Ling, T.-C., Park, A.-H. A., & Chiang, P.-C. (2018). An Overview: Reaction Mechanisms and Modelling of CO2 Utilization via Mineralization. Aerosol and Air Quality Research, 18(4), 829–848. https://doi.org/10.4209/aaqr.2018.03.0093

Pan, Z., Chen, L., Cao, C., Zhang, F., Zhang, H., & Guo, Y. (2024). Optimizing carbonation reaction parameters of calcium carbide slag in acidic/alkaline environment enhancing CO2 mineralization efficiency. Chemical Engineering Journal, 498, 155587. https://doi.org/10.1016/j.cej.2024.155587

Papadakis, V. G. (2000). Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress. Cement and Concrete Research, 30(2), 291–299. https://doi.org/10.1016/S0008-8846(99)00249-5

Papadakis, V. G., Vayenas, C. G., & Fardis, M. N. (1991a). Experimental investigation and mathematical modeling of the concrete carbonation problem. Chemical Engineering Science, 46(5), 1333–1338. https://doi.org/10.1016/0009-2509(91)85060-B

Papadakis, V. G., Vayenas, C. G., & Fardis, M. N. (1991b). Fundamental Modeling and Experimental Investigation of Concrete Carbonation. ACI Materials Journal, 88(4). https://doi.org/10.14359/1863

Pape, C., & Rueda, O. (2024). Carbon Accounting of Recarbonation in Lime Products. European Lime Association. https://eula.eu/resources/carbon-accounting-of-recarbonation-in-lime-products/

Possan, E., Felix, E. F., & Thomaz, W. A. (2016). CO2 uptake by carbonation of concrete during life cycle of building structures. Journal of Building Pathology and Rehabilitation, 1(1), 7. https://doi.org/10.1007/s41024-016-0010-9

Puro. (2022). Carbon removal methods | Carbonated Materials. https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Carbonated%20Materials%20Methodology.pdf

Ragipani, R., Bhattacharya, S., & Suresh, A. K. (2019). Kinetics of steel slag dissolution: From experiments to modelling. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 475(2224), 20180830. https://doi.org/10.1098/rspa.2018.0830

Ragipani, R., Bhattacharya, S., & Suresh, A. K. (2021). A review on steel slag valorisation via mineral carbonation. Reaction Chemistry & Engineering, 6(7), 1152–1178. https://doi.org/10.1039/D1RE00035G

Ragn-Sells, TalTech, University of Tartu, & Estonian University of Life Sciences. (2024, March 7). From waste to valuable products. Oil Shale Ash Upcycling Project. https://osaservice.ee/en/

Rankl, F., & Grimes, P. (2024). RAAC in the UK: Concerns and government response. https://commonslibrary.parliament.uk/research-briefings/cbp-9917/

Rathnakumar, S., & Garg, N. (2024). Multi-modal imaging of the cementitious carbonation front: Evidence for pore refinement. Journal of CO2 Utilization, 90, 102993. https://doi.org/10.1016/j.jcou.2024.102993

Ravikumar, D., Zhang, D., Keoleian, G., Miller, S., Sick, V., & Li, V. (2021). Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit. Nature Communications, 12(1), 855. https://doi.org/10.1038/s41467-021-21148-w

Renforth, P. (2019). The negative emission potential of alkaline materials. Nature Communications, 10(1), 1401. https://doi.org/10.1038/s41467-019-09475-5

RILEM. (2022). 309-MCP: Accelerated Mineral Carbonation for the production of construction materials. https://www.rilem.net/groupe/309-mcp-accelerated-mineral-carbonation-for-the-production-of-construction-materials-442/

Riverse. (2024a). Construction Materials Reuse. Riverse. https://www.riverse.io/methodologies/construction-materials-reuse

Riverse. (2024b). Low Carbon Construction Materials. Riverse. https://www.riverse.io/methodologies/low-carbon-cement

Rosa, L., Becattini, V., Gabrielli, P., Andreotti, A., & Mazzotti, M. (2022). Carbon dioxide mineralization in recycled concrete aggregates can contribute immediately to carbon-neutrality. Resources, Conservation and Recycling, 184, 106436. https://doi.org/10.1016/j.resconrec.2022.106436

Sandford, C., Popstoyanova, Z., Malins, C., Johnson, M., & Lonsdale, J. (2025). Review of carbon removal by enhanced rock weathering. Support to the Development of Methodologies for the Certification of Industrial Carbon Removals with Permanent Storage.

Sanjuán, M. Á., Andrade, C., & Cheyrezy, M. (2003). Concrete carbonation tests in natural and accelerated conditions. Advances in Cement Research, 15(4), 171–180. https://doi.org/10.1680/adcr.2003.15.4.171

Sanjuán, M. Á., Andrade, C., Mora, P., & Zaragoza, A. (2020). Carbon Dioxide Uptake by Cement-Based Materials: A Spanish Case Study. Applied Sciences, 10(1), Article 1. https://doi.org/10.3390/app10010339

Santos, R. M., Van Bouwel, J., Vandevelde, E., Mertens, G., Elsen, J., & Van Gerven, T. (2013). Accelerated mineral carbonation of stainless steel slags for CO2 storage and waste valorization: Effect of process parameters on geochemical properties. International Journal of Greenhouse Gas Control, 17, 32–45. https://doi.org/10.1016/j.ijggc.2013.04.004

Scrivener, K. L., John, V. M., & Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. Cement and Concrete Research, 114, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

Silva, J. V. S., Reis, E. D., de Azevedo, R. C., & Poggiali, F. S. J. (2024). Towards eco-friendly cement-based materials: A review on incorporating oil shale ash. Discover Civil Engineering, 1(1), 23. https://doi.org/10.1007/s44290-024-00027-5

Silva, R. V., Silva, A., Neves, R., & de Brito, J. (2016). Statistical Modeling of Carbonation in Concrete Incorporating Recycled Aggregates. Journal of Materials in Civil Engineering, 28(1), 04015082. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001366

Sirotti, M. (2025). Net-Zero Pathways for European Cement. Bellona EU. https://eu.bellona.org/publication/report-net-zero-pathways-for-european-cement/

Starnoni, M., Dawi, M. A., & Sanchez-Vila, X. (2024). BioReactPy: An open-source software for simulation of microbial-mediated reactive processes in porous media. Applied Computing and Geosciences, 22, 100166. https://doi.org/10.1016/j.acags.2024.100166

Starnoni, M., & Sanchez-Vila, X. (2024). Pore-scale modelling of subsurface biomineralization for carbon mineral storage. Advances in Water Resources, 185, 104641. https://doi.org/10.1016/j.advwatres.2024.104641

Stripple, H., Ljungkrantz, C., Gustafsson, T., & Andersson, R. (2018). CO2 uptake in cement-containing products—Background and calculation models for IPCC implementation. IVL Svenska Miljöinstitutet. https://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-2861

Strunge, T., Renforth, P., & Van der Spek, M. (2022). Towards a business case for CO2 mineralisation in the cement industry. Communications Earth & Environment, 3(1), 59. https://doi.org/10.1038/s43247-022-00390-0

Tanzer, S. E., Blok, K., & Ramírez, A. (2021). Curing time: A temporally explicit life cycle CO2 accounting of mineralization, bioenergy, and CCS in the concrete sector. Faraday Discussions, 230(0), 271–291. https://doi.org/10.1039/D0FD00139B

Thomas, M., & Monkman, S. (2022). The carbonation of recycled concrete aggregate affected by alkali silica reaction. 16th International Conference on Alkali-Aggregate Reaction in Concrete. https://icaarconcrete.org/wp-content/uploads/2024/05/16ICAAR-ThomasM-1.pdf

Trias, R., Ménez, B., le Campion, P., Zivanovic, Y., Lecourt, L., Lecoeuvre, A., Schmitt-Kopplin, P., Uhl, J., Gislason, S. R., Alfreðsson, H. A., Mesfin, K. G., Snæbjörnsdóttir, S. Ó., Aradóttir, E. S., Gunnarsson, I., Matter, J. M., Stute, M., Oelkers, E. H., & Gérard, E. (2017). High reactivity of deep biota under anthropogenic CO2 injection into basalt. Nature Communications, 8(1), 1063. https://doi.org/10.1038/s41467-017-01288-8

UNFCCC. (2012). ACM0005: Increasing the blend in cement production (Version 7.1.0). CDM Methodologies. https://cdm.unfccc.int/methodologies/DB/1AG8O523O2UQD01BAID55YT2LZZ6R0

UNFCCC. (2014). ACM0015: Emission reductions from raw material switch in clinker production (Version 4.0). CDM Methodologies. https://cdm.unfccc.int/methodologies/DB/A8IL4OR2H1FWNDYYOJXCMCAA2JA9FV

UNFCCC. (2020). ACM0003: Partial substitution of fossil fuels in cement or quicklime manufacture (Version 9.0). CDM Methodologies. https://cdm.unfccc.int/methodologies/DB/8U4CEW1DGPRKCIXFKTQ4FURFTPIAZC

UNFCCC. (2024). AM0125: Production of geopolymer cement (Version 1.1). CDM Methodologies. https://cdm.unfccc.int/methodologies/DB/6WEPJYB5IJCKPJ4ISZRYOH8OF4XXNV

Van Roijen, E., Sethares, K., Kendall, A., & Miller, S. A. (2024). The climate benefits from cement carbonation are being overestimated. Nature Communications, 15(1), 4848. https://doi.org/10.1038/s41467-024-48965-z

Verra. (2024). VM0043 CO2 Utilization in Concrete Production, v1.1. Verra. https://verra.org/methodologies/vm0043-co2-utilization-in-concrete-production-v1-1/

Villagran-Zaccardi, Y. A., Ellwood, L., Perumal, P., Torrenti, J. M., Zhao, Z., Bernard, E., Hanein, T., Ling, T. C., Wang, W., Zhang, Z., & Snellings, R. (2024). Carbonated recycled concrete aggregates in construction: Potential and bottlenecks identified by RILEM TC 309-MCP. Materials and Structures, 58(1), 20. https://doi.org/10.1617/s11527-024-02489-6

Vollpracht, A., Gluth, G. J. G., Rogiers, B., Uwanuakwa, I. D., Phung, Q. T., Villagran Zaccardi, Y., Thiel, C., Vanoutrive, H., Etcheverry, J. M., Gruyaert, E., Kamali-Bernard, S., Kanellopoulos, A., Zhao, Z., Martins, I. M., Rathnarajan, S., & De Belie, N. (2024). Report of RILEM TC 281-CCC: Insights into factors affecting the carbonation rate of concrete with SCMs revealed from data mining and machine learning approaches. Materials and Structures, 57(9), 206. https://doi.org/10.1617/s11527-024-02465-0

von Greve-Dierfeld, S., Lothenbach, B., Vollpracht, A., Wu, B., Huet, B., Andrade, C., Medina, C., Thiel, C., Gruyaert, E., Vanoutrive, H., Saéz del Bosque, I. F., Ignjatovic, I., Elsen, J., Provis, J. L., Scrivener, K., Thienel, K.-C., Sideris, K., Zajac, M., Alderete, N., … De Belie, N. (2020). Understanding the carbonation of concrete with supplementary cementitious materials: A critical review by RILEM TC 281-CCC. Materials and Structures, 53(6), 136. https://doi.org/10.1617/s11527-020-01558-w

Wang, F., & Dreisinger, D. (2022). Carbon mineralization with concurrent critical metal recovery from olivine. Proceedings of the National Academy of Sciences of the United States of America, 119(32), e2203937119. https://doi.org/10.1073/pnas.2203937119

Wang, J., & Ma, Y. (2023). A semi-empirical model for predicting carbonation depth of RAC under two-dimensional conditions. REVIEWS ON ADVANCED MATERIALS SCIENCE, 62(1). https://doi.org/10.1515/rams-2023-0115

Wang, S., Wang, Y., Yuan, J., Wang, R., Feng, J. W., Lin, W., He, H., Dai, X., Xu, W., & Zhang, Z. (2024). Research on the carbonation resistance and improvement technology of fully recycled aggregate concrete. Science and Engineering of Composite Materials, 31(1). https://doi.org/10.1515/secm-2024-0022

Wang, X., Yang, Q., Peng, X., & Qin, F. (2024). A Review of Concrete Carbonation Depth Evaluation Models. Coatings, 14(4), Article 4. https://doi.org/10.3390/coatings14040386

Wilson, S., Harrison, A. L., Dipple, G. M., Power, I. M., Barker, S. L. L., Ulrich Mayer, K., Fallon, S. J., Raudsepp, M., & Southam, G. (2014). Offsetting of CO2 emissions by air capture in mine tailings at the Mount Keith Nickel Mine, Western Australia: Rates, controls and prospects for carbon neutral mining. International Journal of Greenhouse Gas Control, 25, 121–140. https://doi.org/10.1016/j.ijggc.2014.04.002

Wu, S., Shao, Z., Andrew, R. M., Bing, L., Wang, J., Niu, L., Liu, Z., & Xi, F. (2024). Global CO2 uptake by cement materials accounts 1930–2023. Scientific Data, 11(1), 1409. https://doi.org/10.1038/s41597-024-04234-8

Xi, F., Davis, S. J., Ciais, P., Crawford-Brown, D., Guan, D., Pade, C., Shi, T., Syddall, M., Lv, J., Ji, L., Bing, L., Wang, J., Wei, W., Yang, K.-H., Lagerblad, B., Galan, I., Andrade, C., Zhang, Y., & Liu, Z. (2016). Substantial global carbon uptake by cement carbonation. Nature Geoscience, 9(12), 880–883. https://doi.org/10.1038/ngeo2840

Xiao, J., Zhang, H., Tang, Y., Deng, Q., Wang, D., & Poon, C. (2022). Fully utilizing carbonated recycled aggregates in concrete: Strength, drying shrinkage and carbon emissions analysis. Journal of Cleaner Production, 377, 134520. https://doi.org/10.1016/j.jclepro.2022.134520

Yan, Y., Guanbao, T., Ling, W., Suping, C., & Yin, C. (2018). Difference between natural and accelerated carbonation of concrete at 2 % CO2 and 20 % CO2. Revista Romana de Materiale/ Romanian Journal of Materials, 48, 70–75.

Ye, H., Liu, Q., Bao, Q., Wang, Z., Xie, Y., Michelle, T., Zhao, W., & Xian, C. (2025). Review on in-situ CO2 mineralization sequestration: Mechanistic understanding and research frontiers. International Journal of Coal Science & Technology, 12(1), 15. https://doi.org/10.1007/s40789-025-00755-8

Zhang, D., Cai, X., & Shao, Y. (2016). Carbonation Curing of Precast Fly Ash Concrete. Journal of Materials in Civil Engineering, 28(11), 04016127. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001649

Zhang, D., Ghouleh, Z., & Shao, Y. (2017a). Review on carbonation curing of cement-based materials. Journal of CO2 Utilization, 21, 119–131. https://doi.org/10.1016/j.jcou.2017.07.003

Zhang, D., Ghouleh, Z., & Shao, Y. (2017b). Review on carbonation curing of cement-based materials. Journal of CO2 Utilization, 21, 119–131. https://doi.org/10.1016/j.jcou.2017.07.003

Zhang, D., & Shao, Y. (2016). Early age carbonation curing for precast reinforced concretes. Construction and Building Materials, 113, 134–143. https://doi.org/10.1016/j.conbuildmat.2016.03.048

Zhang, K., & Xiao, J. (2018). Prediction model of carbonation depth for recycled aggregate concrete. Cement and Concrete Composites, 88, 86–99. https://doi.org/10.1016/j.cemconcomp.2018.01.013

Zhang, K., Yio, M., Wong, H., & Buenfeld, N. (2024). Development of more accurate methods for determining carbonation depth in cement-based materials. Cement and Concrete Research, 175, 107358. https://doi.org/10.1016/j.cemconres.2023.107358

Zhang, N., Zhang, D., Zuo, J., Miller, T. R., Duan, H., & Schiller, G. (2022). Potential for CO2 mitigation and economic benefits from accelerated carbonation of construction and demolition waste. Renewable and Sustainable Energy Reviews, 169, 112920. https://doi.org/10.1016/j.rser.2022.112920

Zhang, T., Cui, J., Chen, M., Yang, J., Yan, Z., & Zhang, M. (2025). Durability of concrete containing carbonated recycled aggregates: A comprehensive review. Cement and Concrete Composites, 156, 105865. https://doi.org/10.1016/j.cemconcomp.2024.105865

Zhang, X., Chen, J., Jiang, J., Li, J., Tyagi, R. D., & Surampalli, R. Y. (2020). The potential utilization of slag generated from iron- and steelmaking industries: A review. Environmental Geochemistry and Health, 42(5), 1321–1334. https://doi.org/10.1007/s10653-019-00419-y

Zhao, Z., Courard, L., Groslambert, S., Jehin, T., Léonard, A., & Xiao, J. (2020). Use of recycled concrete aggregates from precast block for the production of new building blocks: An industrial scale study. Resources, Conservation and Recycling, 157, 104786. https://doi.org/10.1016/j.resconrec.2020.104786