CO_2 as a Performance Enhancing Admixture in Ready Mixed Concrete

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CARBON CURE™

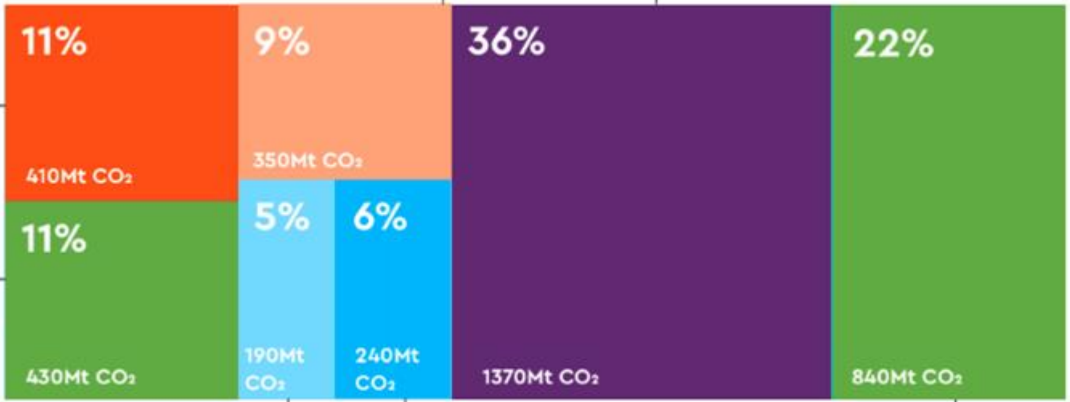
ACTIONS TO A NET ZERO FUTURE

Savings in clinker production
- thermal efficiency
- savings from waste fuels ("alternative fuels")
- use of decarbonated raw materials
- use of hydrogen as a fuel

Savings in cement and binders
- Portland clinker cement substitution. Also expressed through clinker binder ratio
- alternatives to Portland clinker cements

Carbon capture and utilisation/storage
- carbon capture at cement plants

PERCENTAGE CONTRIBUTION TO NET ZERO AND CO_2 EMISSION SAVINGS IN 2050

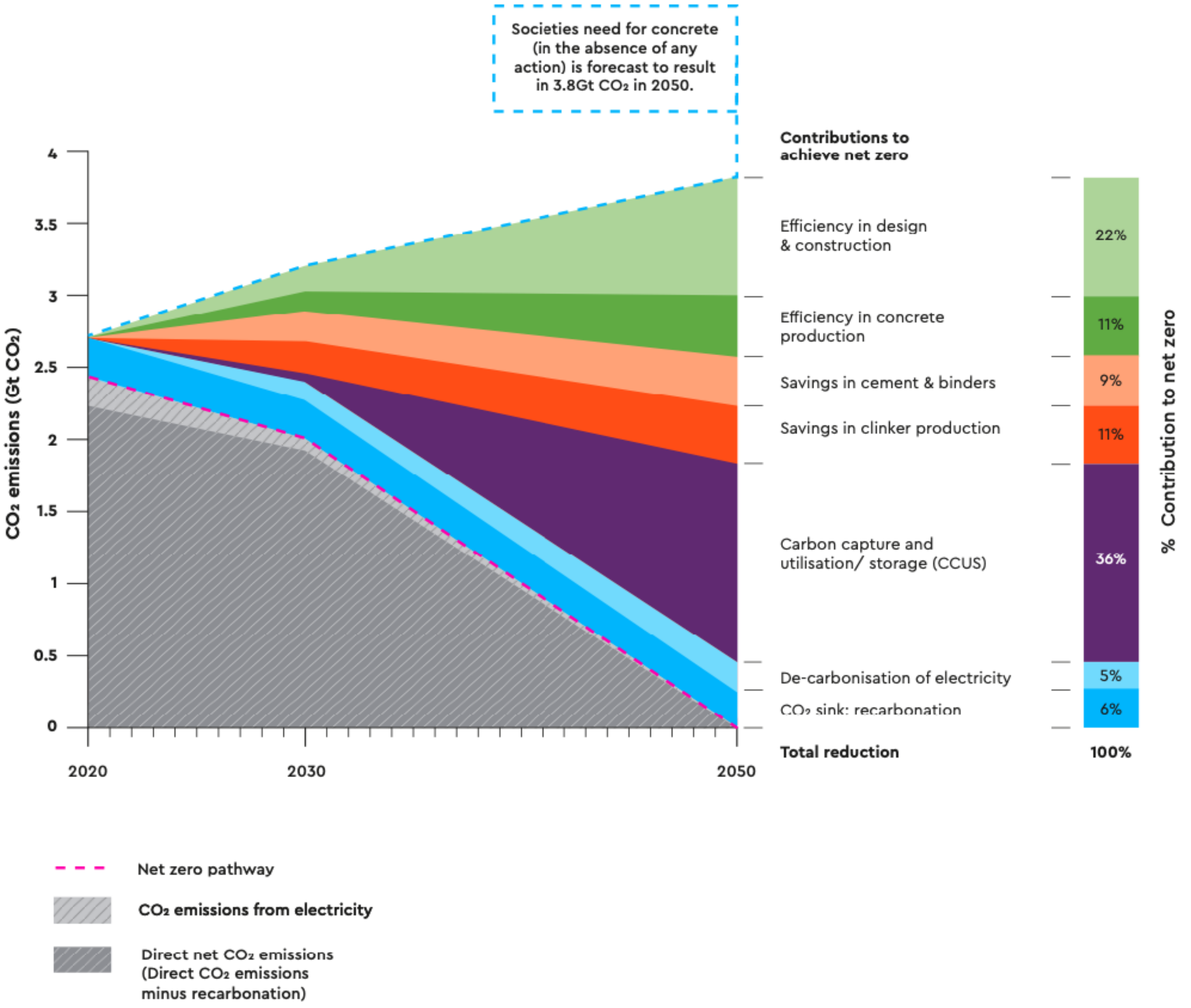


Efficiency in concrete production
- optimised mix design
- optimisation of constituents
- continue to industrialise manufacturing
- quality control

Decarbonisation of electricity
- decarbonisation of electricity used at both cement plants and in concrete production

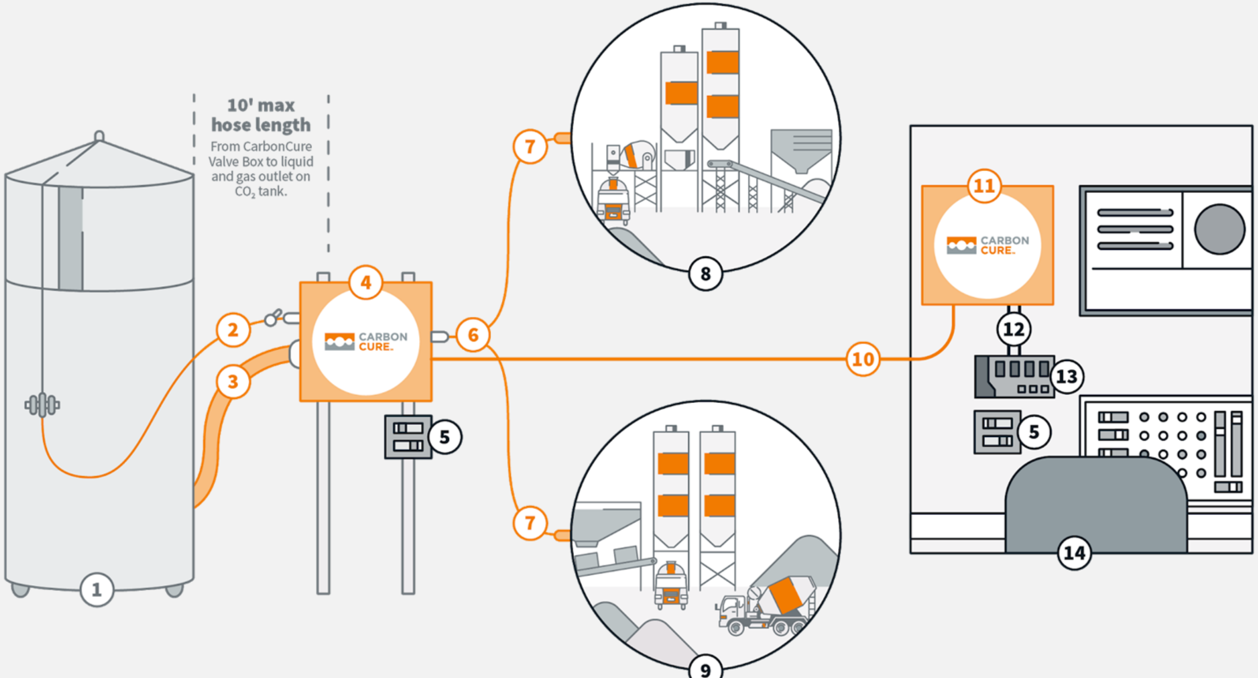
CO_2 sink: recarbonation
- natural uptake of CO_2 in concrete – a carbon sink

Efficiency in design and construction
- client brief to designers to enable optimisation
- design optimisation
- construction site efficiencies
- re-use and lifetime extension


Societies need for concrete (in the absence of any action) is forecast to result in 3.8Gt CO₂ in 2050.
CO₂ emissions (Gt CO₂)
4
3.5
3
2.5
2
1.5
1
0.5
0
2020
2030
2050
Contributions to achieve net zero
Efficiency in design & construction
Efficiency in concrete production
Savings in cement & binders
Savings in clinker production
Carbon capture and utilisation/ storage (CCUS)
De-carbonisation of electricity
CO₂ sink: recarbonation
Total reduction
22%
11%
9%
11%
36%
5%
6%
100%
% Contribution to net zero
Net zero pathway
CO₂ emissions from electricity
Direct net CO₂ emissions (Direct CO₂ emissions minus recarbonation)

CO2 utilization in Ready Mix

Installation overview



Orange: Supplied by CarbonCure
Black: Supplied by Concrete Producer
Grey: Supplied by Gas Company

1. **Bulk CO_2 Tank** Sized according to anticipated CO_2 usage
2. **Gas CO_2 Transfer Line**
3. **Liquid CO_2 Transfer Line**
4. **CarbonCure Valve Box**
5. **120 VAC Electrical Supply** (5A breaker)
6. **CO_2 Snow Discharge Hoses** 60' max hose length
7. **CO_2 Snow Discharge Nozzles** Mounted to inject inside central mixer or in loading area for dry batch
8. **Ready Mix Plant Central Mixer**
9. **Dry Batch Loading Area**
10. **Communication Cable** Variable Length
11. **CarbonCure Control Box**
12. **18AWG Comm Wires**
13. **Batching Junction Box** Open admixture feed card and pulse card
14. **Control Room**


WHO KNEW THAT POURING CONCRETE COULD BE LIKE PLANTING TREES?
CARBON CURE
CARBON CURE
Innovative CO2 Technology

Admixture Analogy

Batch Controller

CO_2 Supply

Admix Supply

CO_2 Dispensing

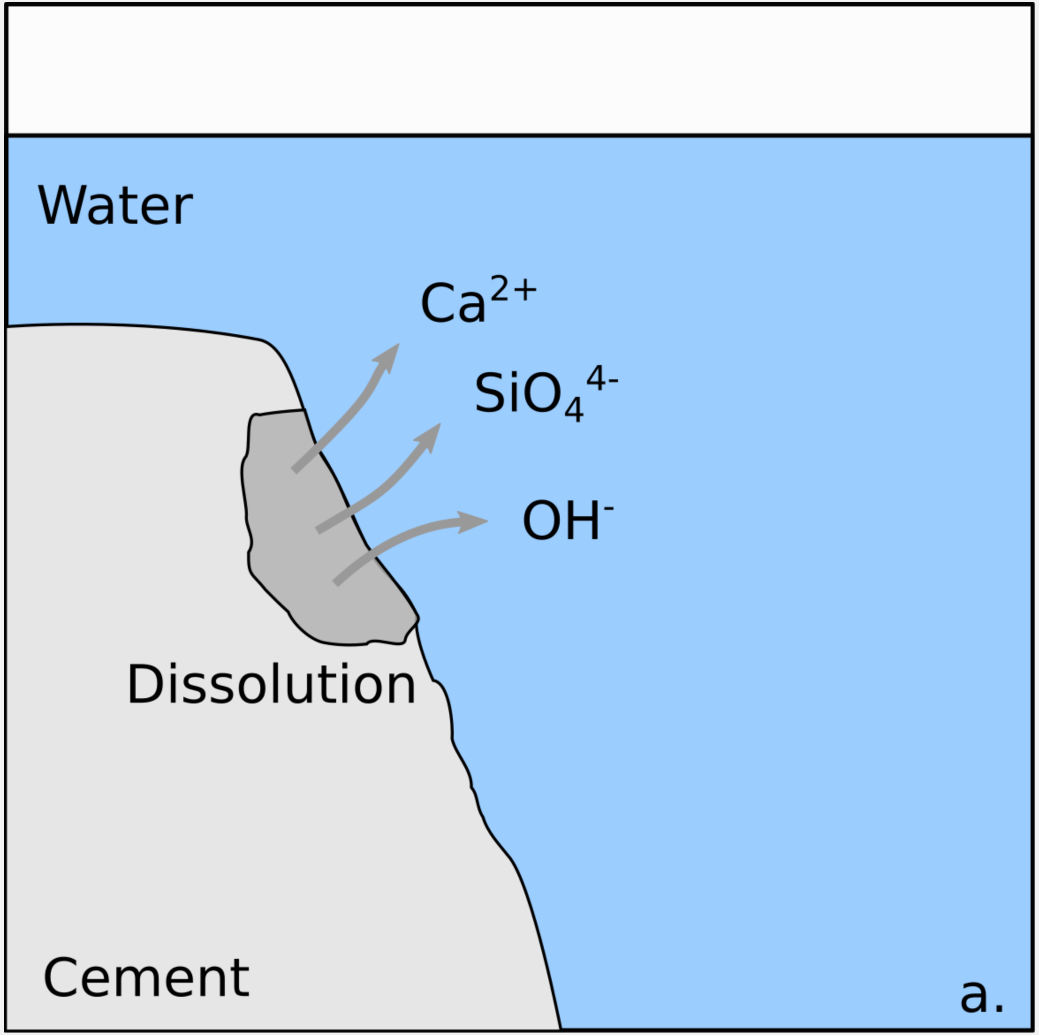
Admix Dispensing

Product

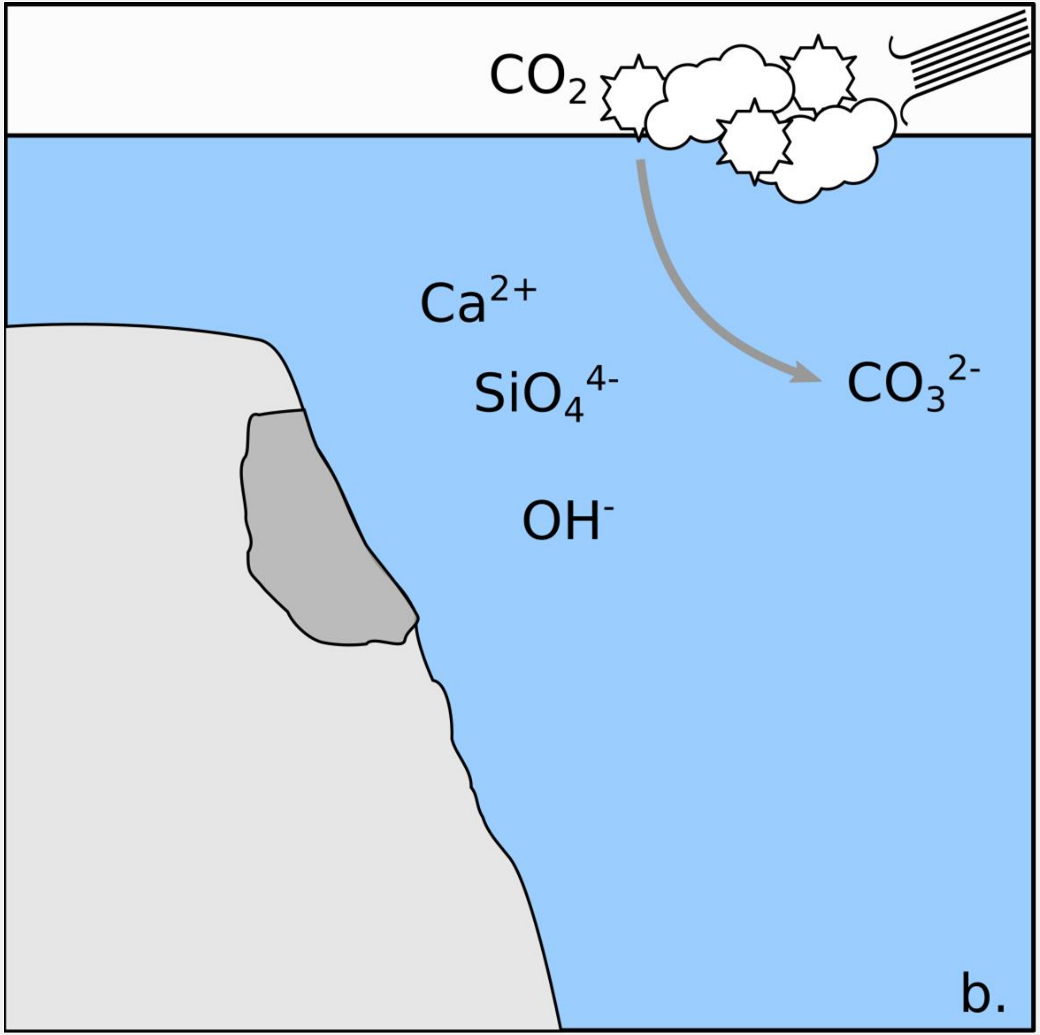
CO_2 Injection
CARBON
CURE™

MECHANISM

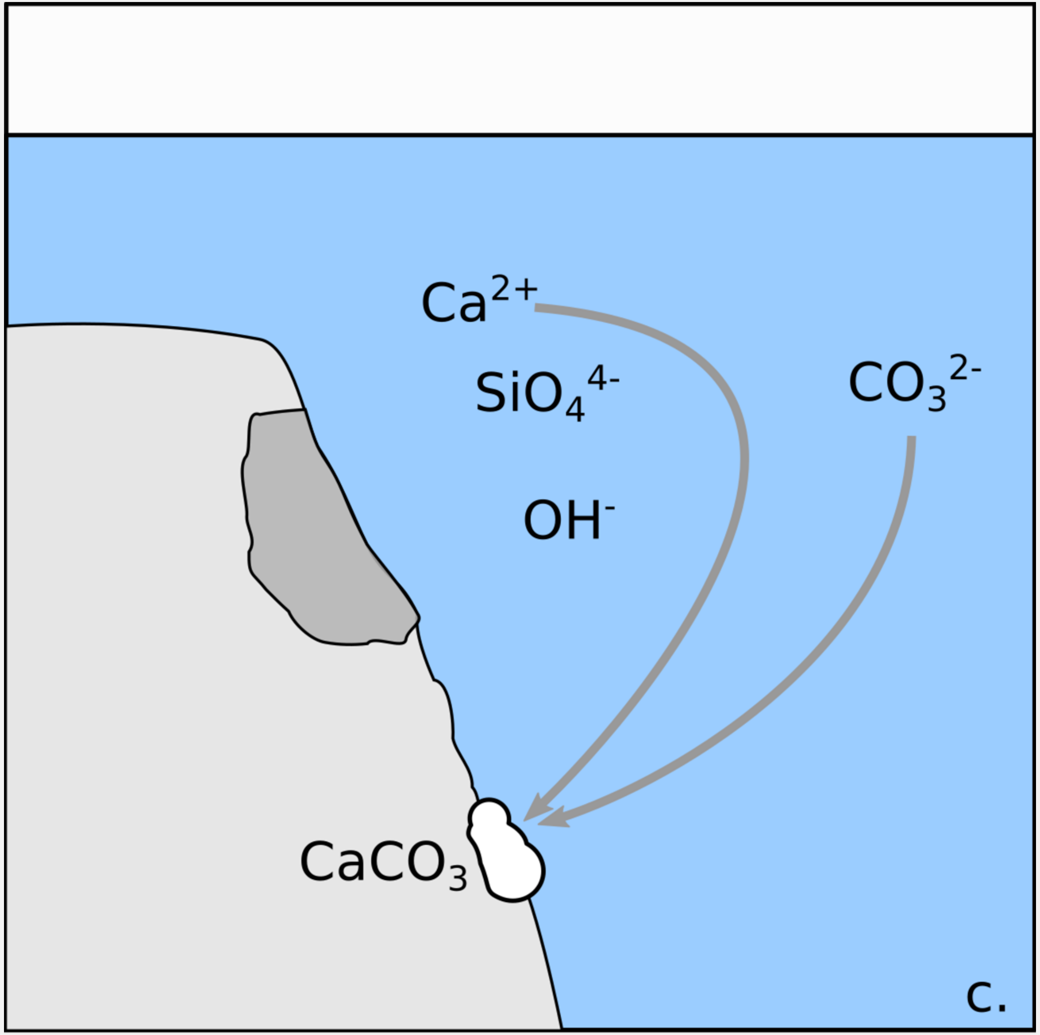
Dissolution



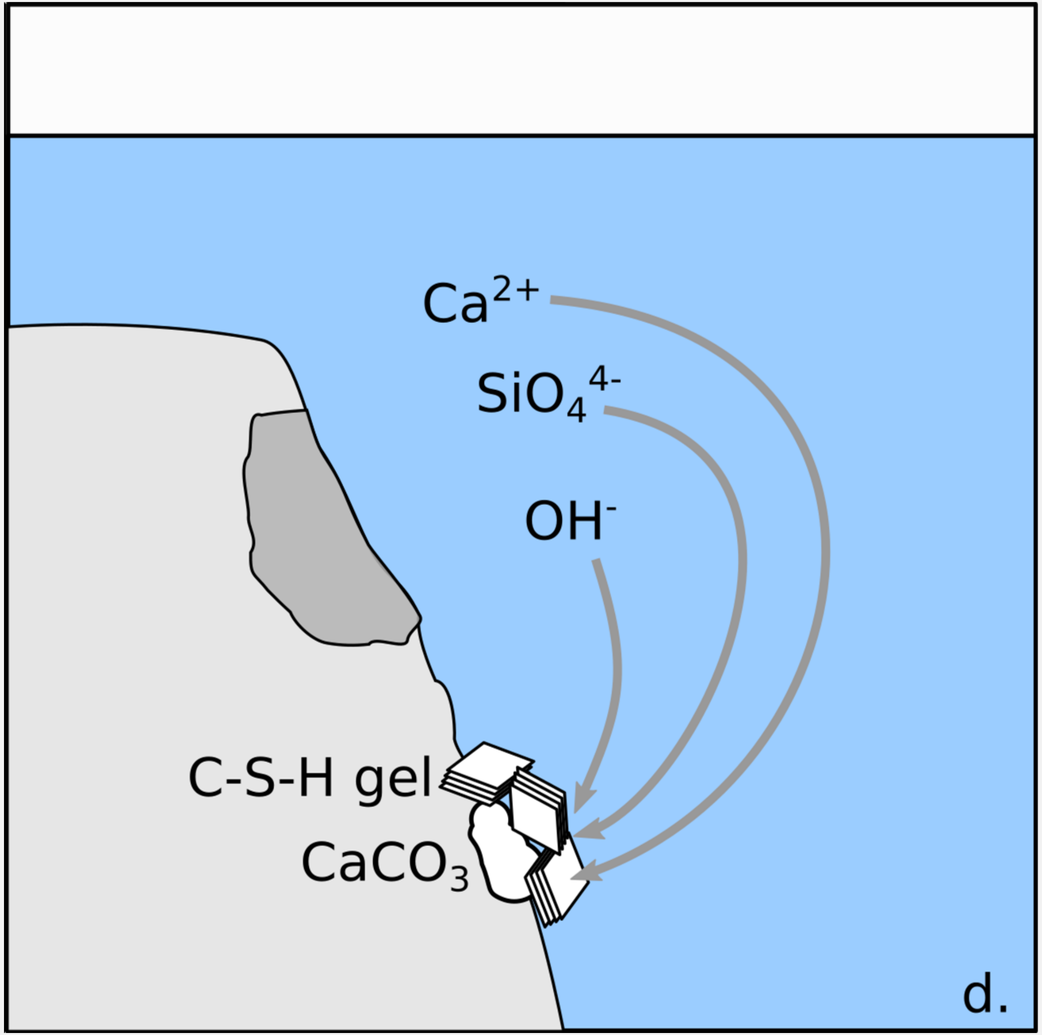
CO_2 addition



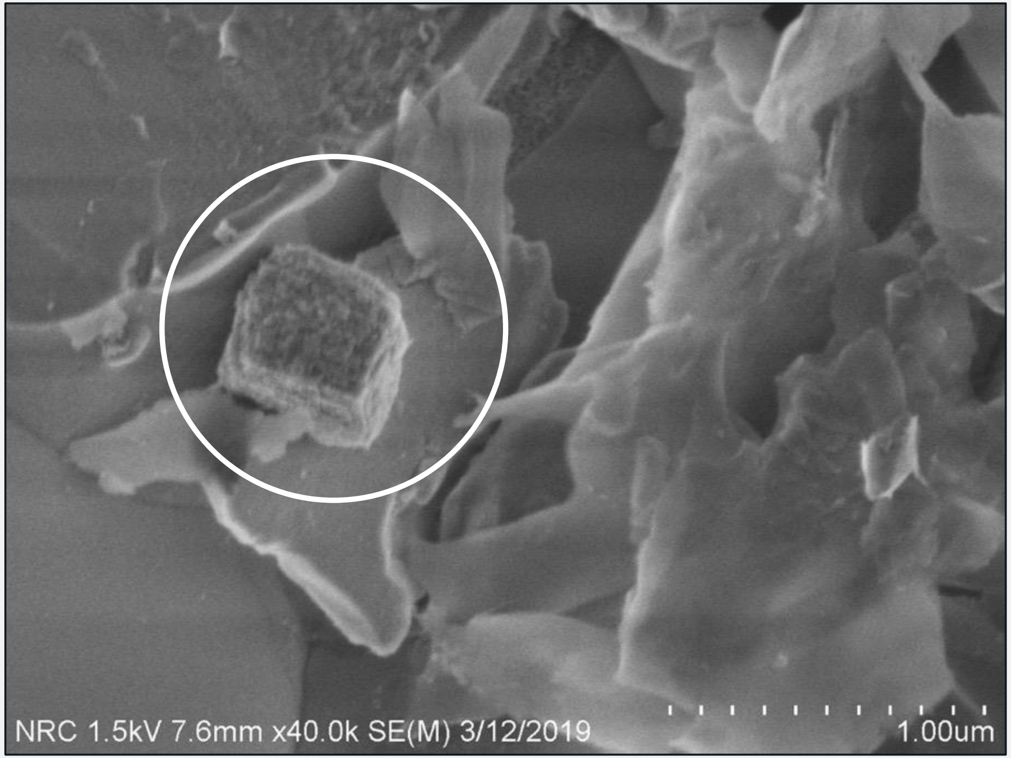
CO_2 mineralization



Hydration



Converting CO_2 to a Mineral



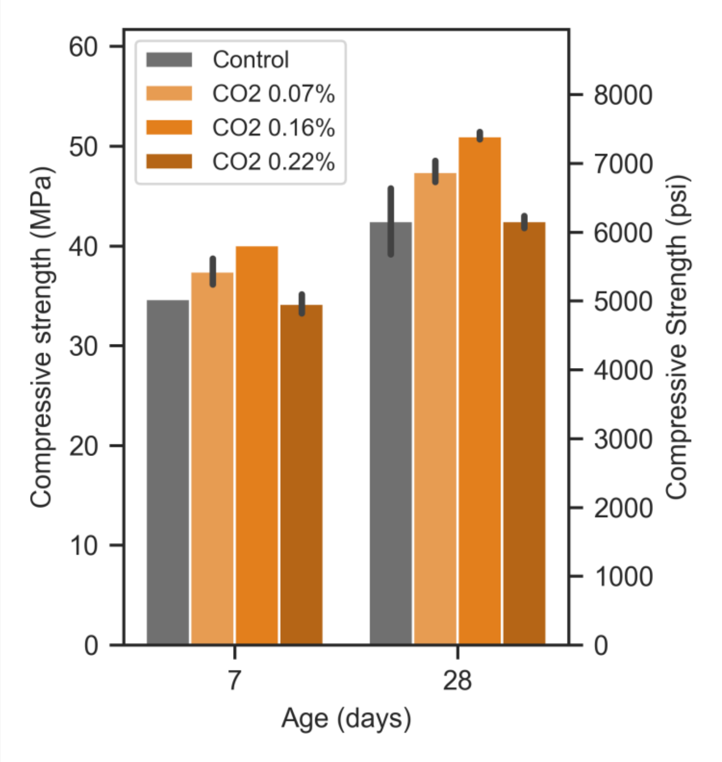
Carbonate product formed with dimensions around **400 nm**

The carbonate mineralization reaction leads to the in situ creation of **nanoscale calcium carbonate** that acts as nucleation sites for the hydration process.

Compressive strength can be increased.

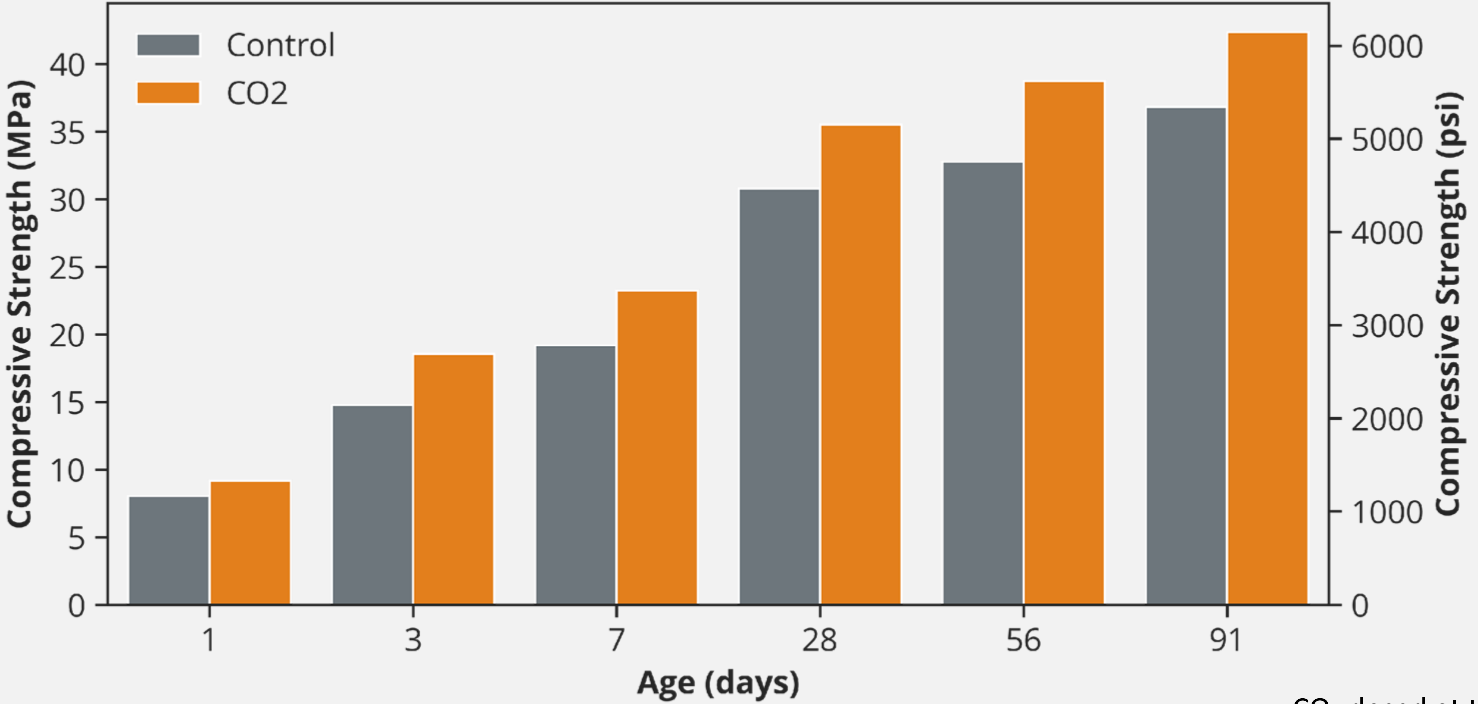
Pilot study - dosages

Pilot work established that a dose of CO_2 added to concrete during batching could lead to compressive strength improvements both at early and later ages.



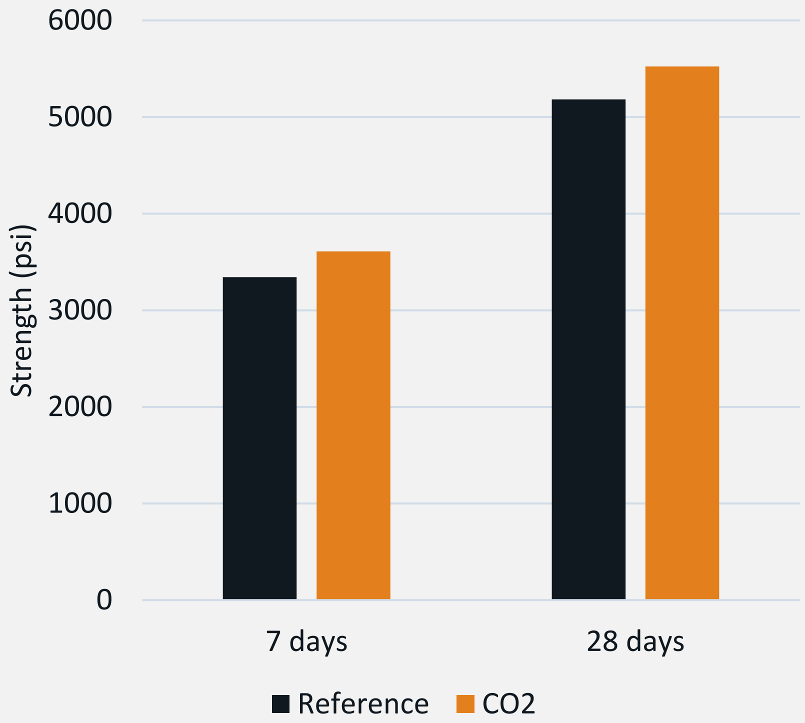
Potential for Strength Gains

2014 Pilot work
25 MPa mix
20% slag



CO_2 dosed at the wash rack

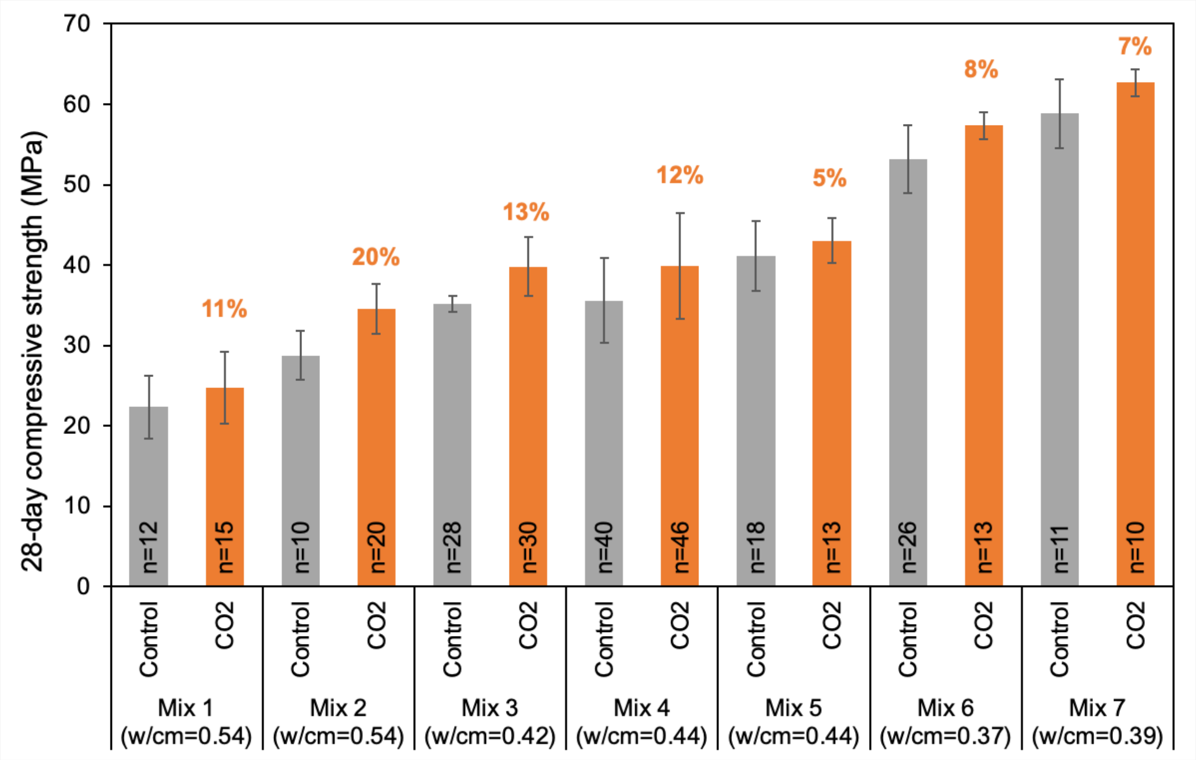
Example



- Design strength 4500 psi
- 564 pcy binder comprising 68% cement, 17% slag, 15% fly ash
- Dose of 0.2% CO_2
- No impact on air or slump
- Strength improved 8% at 7 days and 7% at 28 days
- Cement efficiency increased from 13.5 to 14.4 psi/lb cem

Compatibility

Across the installation base the technology has been used across full range of cement types and sources, SCMs, binder contents, w/cm, and admixtues,



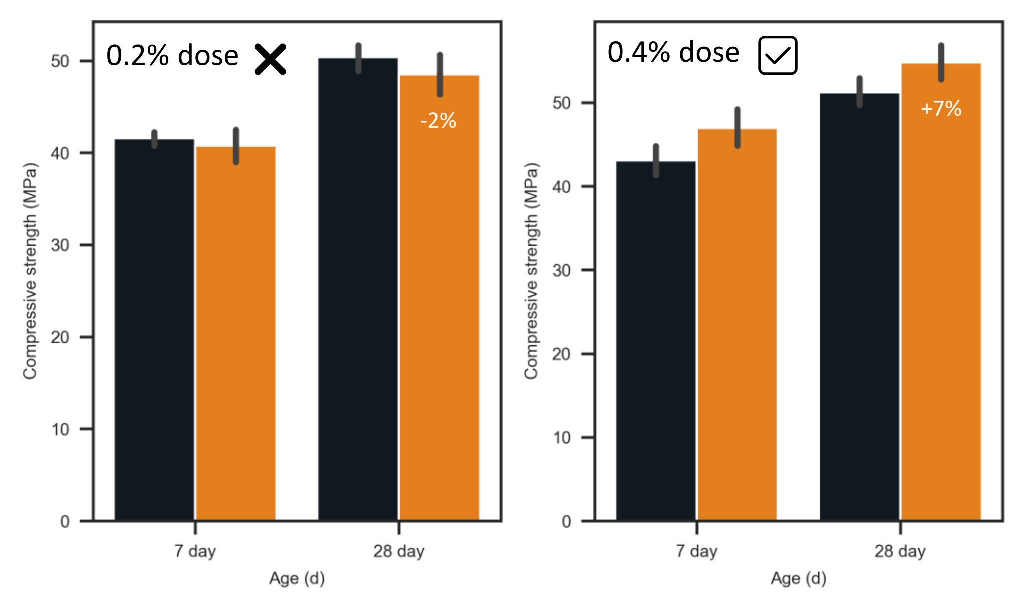
Response with PLC

High limestone contents have resulted in higher dosages

- Typical doses of 0.05% to 0.3% in Type I/II
- Seeing responses above 0.3% in PLC

Example

- 30 MPa mix design
- European CEM II/A-L 42.5
- 14% limestone



0.2% dose	Samples	28d Strength
Reference	9	50.4
CO_2	6	48.3

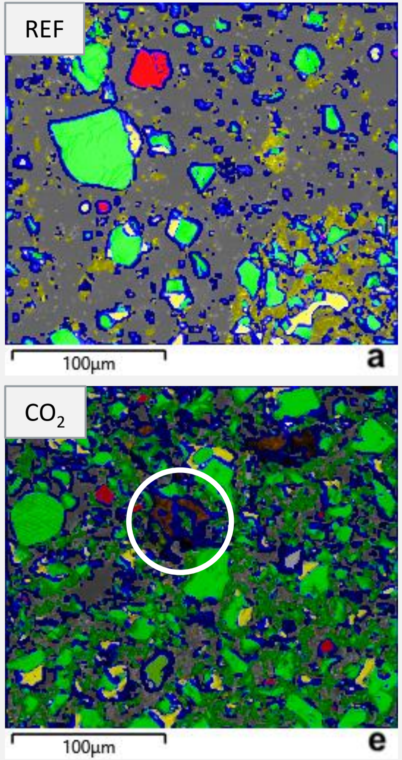
0.4% dose	Samples	28d Strength
Reference	29	51.2
CO_2	24	54.8

How do strength gains arise?

- Paste, activated with CO_2
- Hydration arrest 5 min
- Phase segmentation of BSE micrographs

- Silicates
- Aluminates
- CH, C-S-H
- Limestone
- In-situ $CaCO_3$
- epoxy mount

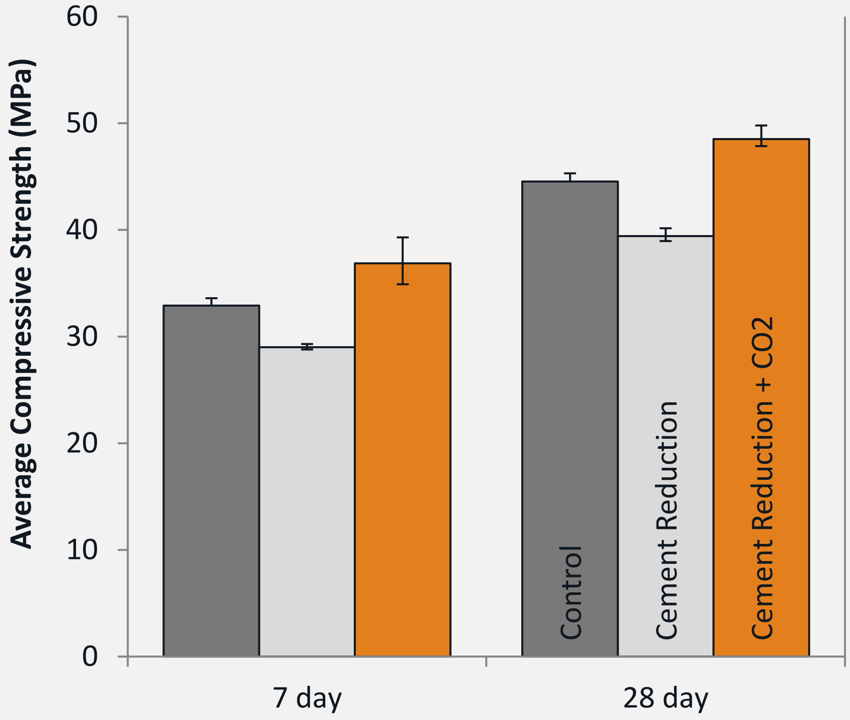
Submitted for publication



Ca/Si LD CSH	REF	CO_2	Relative
5 min	**2.35**	**1.67**	**-29%**
1 day	1.38	1.37	-
7 days	1.62	1.72	-
28 days	1.71	1.65	-

Ca/Si HD CSH	REF	CO_2	Relative
1 day	**2.15**	**1.64**	**-24%**
7 days	2.44	2.38	-
28 days	2.55	2.35	-

Added Strength Allows Mix Adjustment



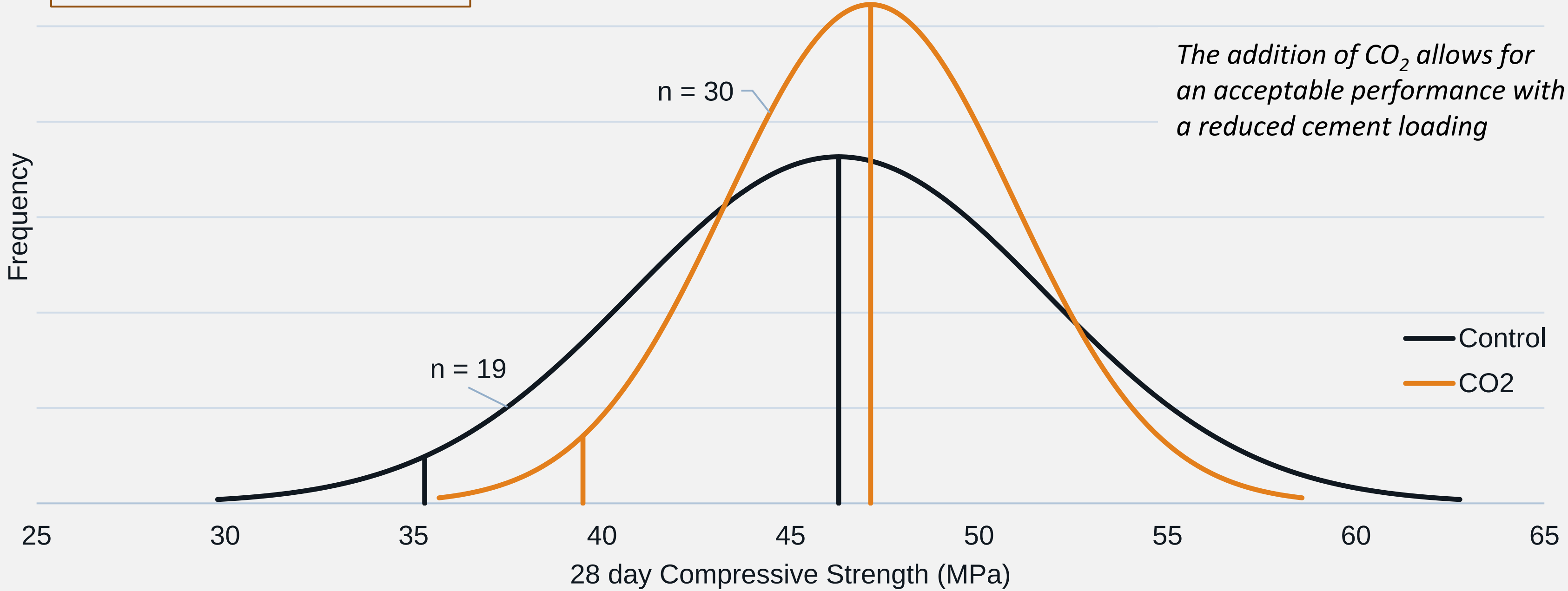
Producer used CO_2 addition to compensate for a 5% reduction in the cement content of the mix yet maintain the compressive strength.

	Reference	Reduced Binder	Reduced Binder + CO2
Cement ($kg\ m^{-3}$)	360	342	342
Cement intensity ($kg\ m^{-3}\ MPa^{-1}$)	8.1	8.7	7.0
Clinker intensity ($kg\ m^{-3}\ MPa^{-1}$)	7.4	8.0	6.5

Extended Production Data

35 MPa mix design
Cement reduction 5.5%

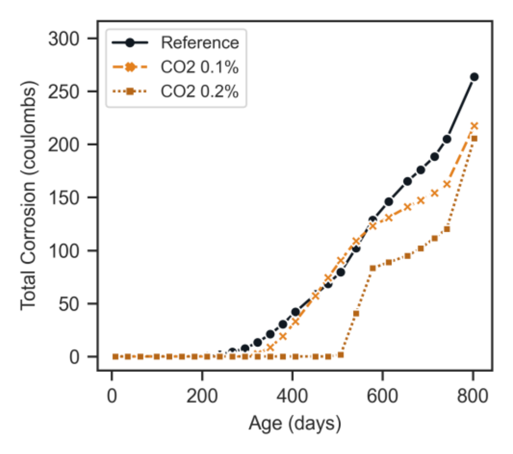
Avoided CO_2 around 138 kg load

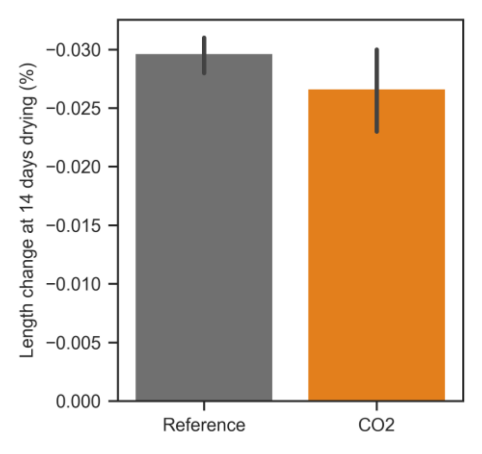


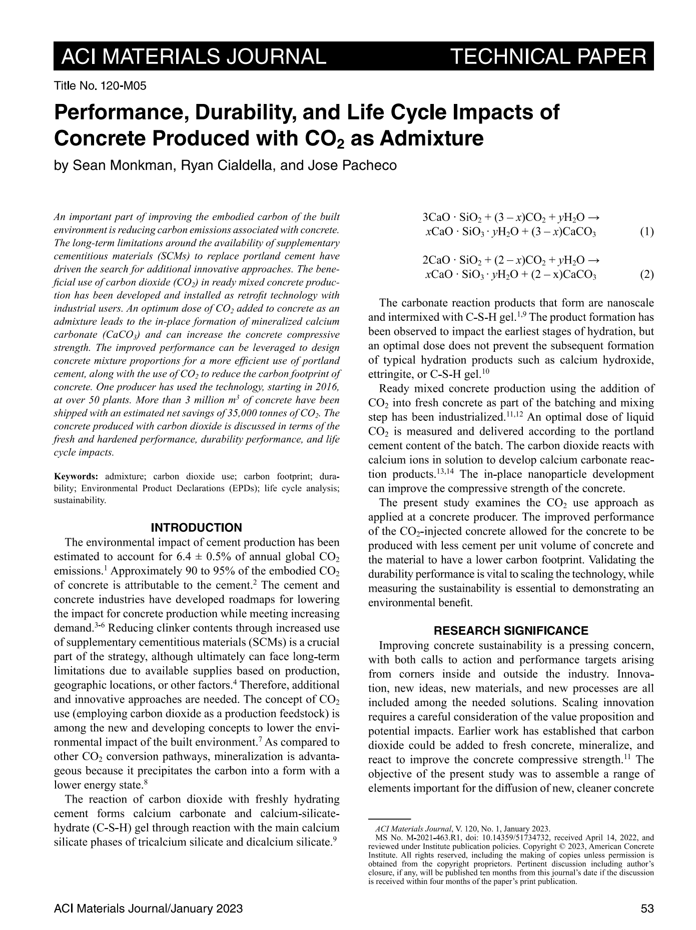
The addition of CO_2 allows for an acceptable performance with a reduced cement loading

Durability

The CO_2 mineralization can increase the cement efficiency but does not negatively impact durability







ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 120-M05

Performance, Durability, and Life Cycle Impacts of Concrete Produced with CO_2 as Admixture

by Sean Monkman, Ryan Cialdella, and Jose Pacheco

An important part of improving the embodied carbon of the built environment is reducing carbon emissions associated with concrete. The long-term limitations around the availability of supplementary cementitious materials (SCMs) to replace portland cement have driven the search for additional innovative approaches. The beneficial use of carbon dioxide (CO_2) in ready mixed concrete production has been developed and installed as retrofit technology with industrial users. An optimum dose of CO_2 added to concrete as an admixture leads to the in-place formation of mineralized calcium carbonate ($CaCO_3$) and can increase the concrete compressive strength. The improved performance can be leveraged to design concrete mixture proportions for a more efficient use of portland cement, along with the use of CO_2 to reduce the carbon footprint of concrete. One producer has used the technology, starting in 2016, at over 50 plants. More than 3 million m^3 of concrete have been shipped with an estimated net savings of 35,000 tonnes of CO_2. The concrete produced with carbon dioxide is discussed in terms of the fresh and hardened performance, durability performance, and life cycle impacts.

Keywords: admixture; carbon dioxide use; carbon footprint; durability; Environmental Product Declarations (EPDs); life cycle analysis; sustainability.

INTRODUCTION

The environmental impact of cement production has been estimated to account for 6.4 ± 0.5% of annual global CO_2 emissions.[1] Approximately 90 to 95% of the embodied CO_2 of concrete is attributable to the cement.[2] The cement and concrete industries have developed roadmaps for lowering the impact for concrete production while meeting increasing demand.[3-6] Reducing clinker contents through increased use of supplementary cementitious materials (SCMs) is a crucial part of the strategy, although ultimately can face long-term limitations due to available supplies based on production, geographic locations, or other factors.[4] Therefore, additional and innovative approaches are needed. The concept of CO_2 use (employing carbon dioxide as a production feedstock) is among the new and developing concepts to lower the environmental impact of the built environment.[7] As compared to other CO_2 conversion pathways, mineralization is advantageous because it precipitates the carbon into a form with a lower energy state.[8]

The reaction of carbon dioxide with freshly hydrating cement forms calcium carbonate and calcium-silicate-hydrate (C-S-H) gel through reaction with the main calcium silicate phases of tricalcium silicate and dicalcium silicate.[9]

$$3CaO \cdot SiO_2 + (3-x)CO_2 + yH_2O \rightarrow xCaO \cdot SiO_3 \cdot yH_2O + (3-x)CaCO_3 \quad (1)$$

$$2CaO \cdot SiO_2 + (2-x)CO_2 + yH_2O \rightarrow xCaO \cdot SiO_3 \cdot yH_2O + (2-x)CaCO_3 \quad (2)$$

The carbonate reaction products that form are nanoscale and intermixed with C-S-H gel.[1,9] The product formation has been observed to impact the earliest stages of hydration, but an optimal dose does not prevent the subsequent formation of typical hydration products such as calcium hydroxide, ettringite, or C-S-H gel.[10]

Ready mixed concrete production using the addition of CO_2 into fresh concrete as part of the batching and mixing step has been industrialized.[11,12] An optimal dose of liquid CO_2 is measured and delivered according to the portland cement content of the batch. The carbon dioxide reacts with calcium ions in solution to develop calcium carbonate reaction products.[13,14] The in-place nanoparticle development can improve the compressive strength of the concrete.

The present study examines the CO_2 use approach as applied at a concrete producer. The improved performance of the CO_2-injected concrete allowed for the concrete to be produced with less cement per unit volume of concrete and the material to have a lower carbon footprint. Validating the durability performance is vital to scaling the technology, while measuring the sustainability is essential to demonstrating an environmental benefit.

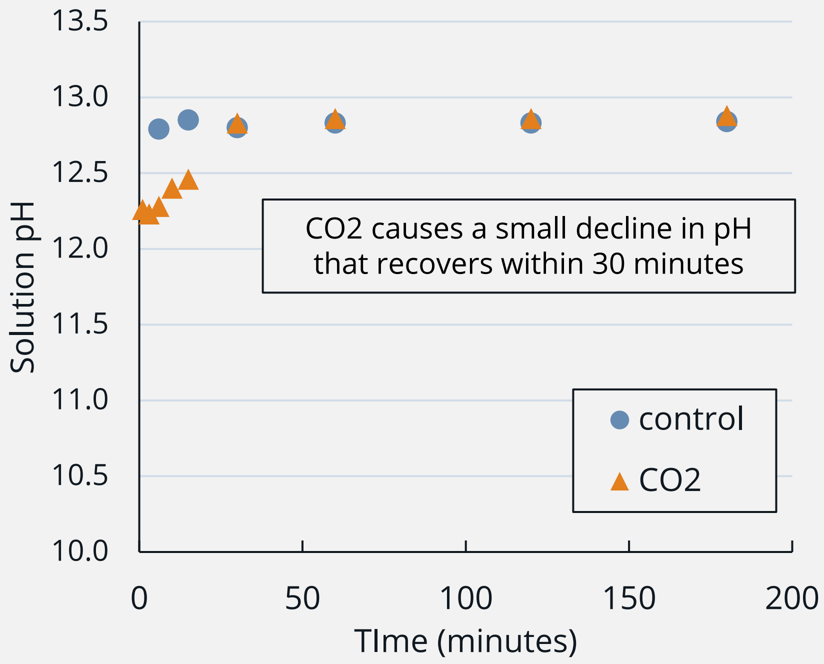
RESEARCH SIGNIFICANCE

Improving concrete sustainability is a pressing concern, with both calls to action and performance targets arising from corners inside and outside the industry. Innovation, new ideas, new materials, and new processes are all included among the needed solutions. Scaling innovation requires a careful consideration of the value proposition and potential impacts. Earlier work has established that carbon dioxide could be added to fresh concrete, mineralize, and react to improve the concrete compressive strength.[11] The objective of the present study was to assemble a range of elements important for the diffusion of new, cleaner concrete

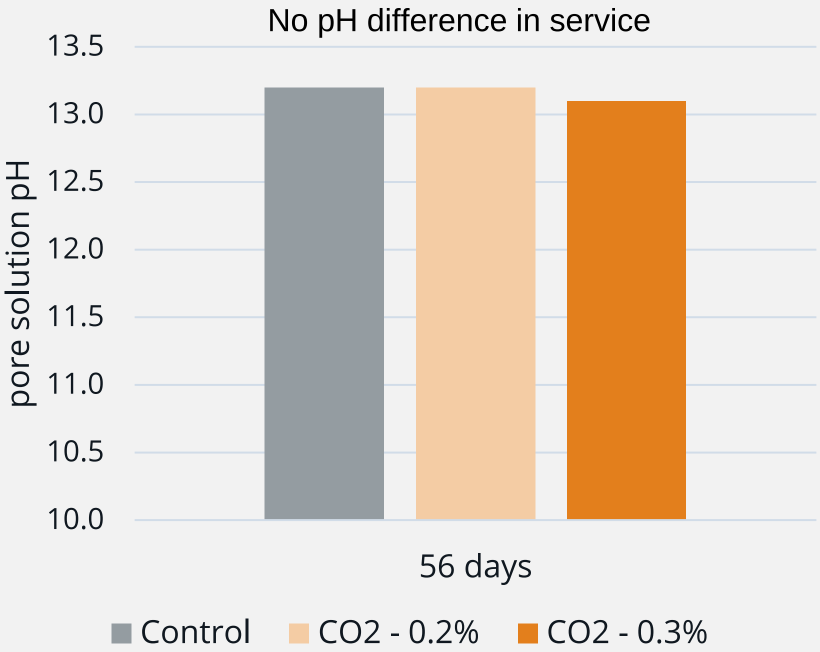
ACI Materials Journal, V. 120, No. 1, January 2023.
MS No. M-2021-463.R1, doi: 10.14359/51734732, received April 14, 2022, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published ten months from this journal's date if the discussion is received within four months of the paper's print publication.

No Impact on Pore Solution Alkalinity

Early hydration, cement paste, lab study



Industrially produced, pore solution @ 56d



LIFE CYCLE ANALYSIS

Life Cycle Impacts

- Emissions associated with capture and compression of the CO_2
- Emissions associated with CO_2 transport
- Manufacture, transport and operations of the hardware

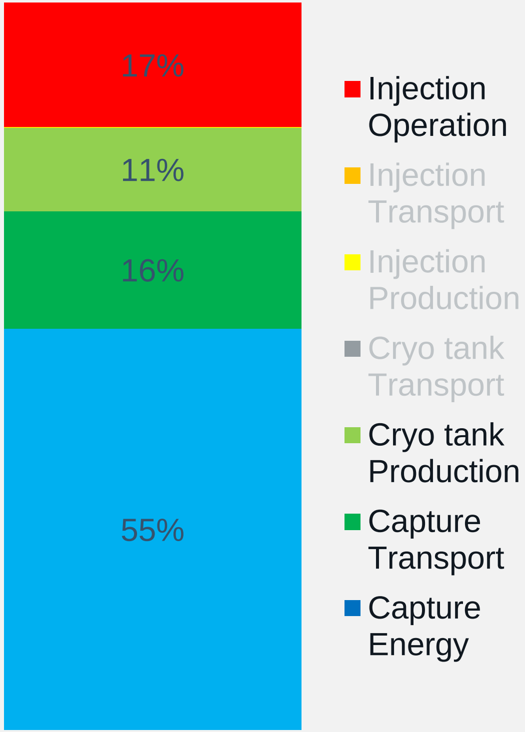
Estimated Impacts

Assuming
US grid emission
0.336 kg CO_2/kWh

Aspect	Emission relative to CO_2 dosed
CO_2 Capture*	6.7%
CO_2 Transport	2.0%
Cryogenic tank creation	1.4%
Cryogenic tank transport	0.002%
Hardware creation	0.011%
Hardware transport	0.002%
Hardware operation*	2.1%
Total	**12.2%**
Total including vented	**22.2%**

* Sensitive to grid emissions

1 kg dosed
222 g emitted
900 g mineralized
778 g net removed

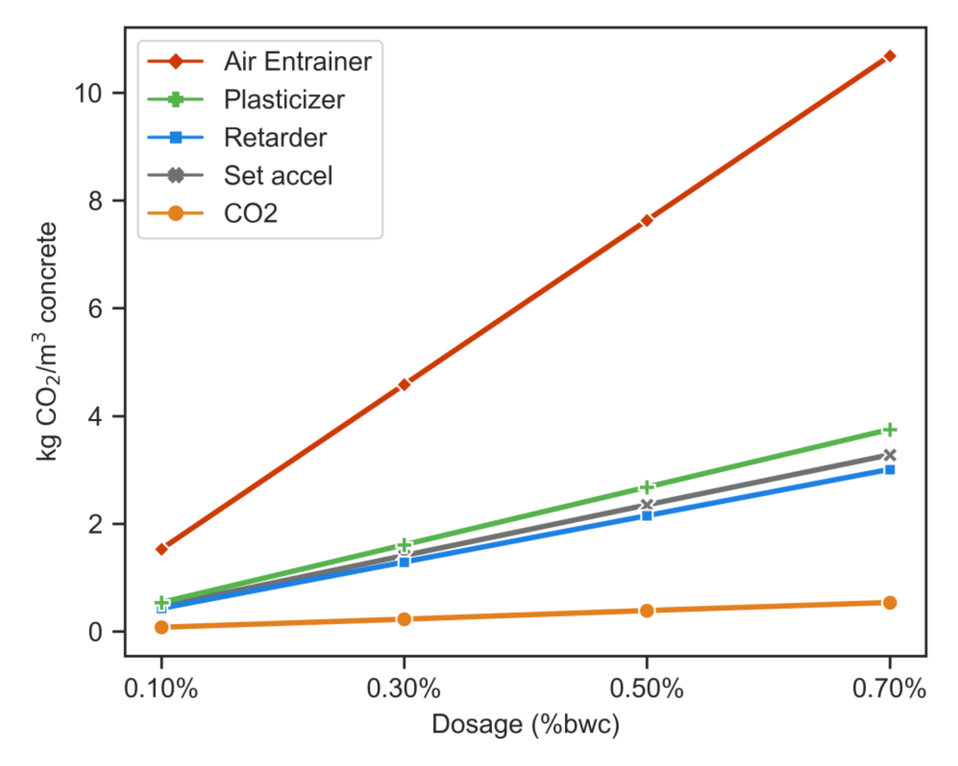


What is the carbon footprint of CO_2?

Cement content 350 kg/m[3]

The carbon footprint of CO_2 injection is considerably lower than the CO_2 footprint of other chemical admixtures

- Admix data from EFCA EPDs
- In plot, admix impacts are underestimated, only using A1-A3 in LCA
- In plot, CO_2 impacts are overestimated – excludes mineralized



Carbon Removal

- Mineralization and cement reduction can be combined to within a Carbon Dioxide Removal (CDR) methodology
- LCA supports the creation of Verified Carbon Units (VCUs) that can be sold on the Voluntary Carbon Market (VCM)

Verified Carbon Standard

VCS Methodology

VM0043

Methodology for CO_2 Utilization in Concrete Production

Version 1.0

April 2021

Sectoral Scopes 4 & 6

Closing thoughts

Reference Project:

Amazon HQ2 - Arlington, VA

Helping Amazon achieve net zero carbon by 2040

> *“The mixes have outperformed even my own expectations and I have very high expectations. I don't believe we had one low break on that project. They performed fantastically.”*
>
> **Jim Martinoski, Vice President of Miller & Long Co., Inc.**

Owner:
Amazon

Concrete Supplier:
Miller & Long Co., Inc.

Concrete Supplied:
106,555 yd^3

Contractor:
Clark Construction

Structural Engineer:
Thornton Tomasetti

Architect:
ZGF Architects

Est. CO_2 Savings:
1,000+ metric tons

CO_2 Savings Equivalent:
1,100+ acres of forest absorbing CO_2 per year

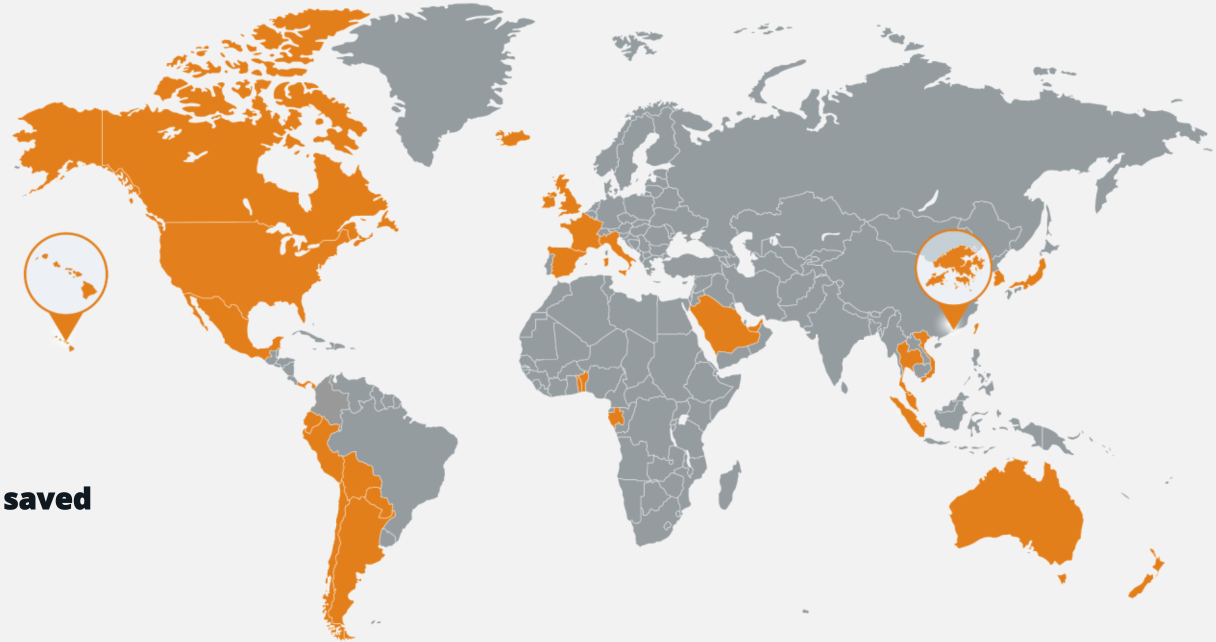
Global Adoption

Location of CO_2 mineralized concrete suppliers

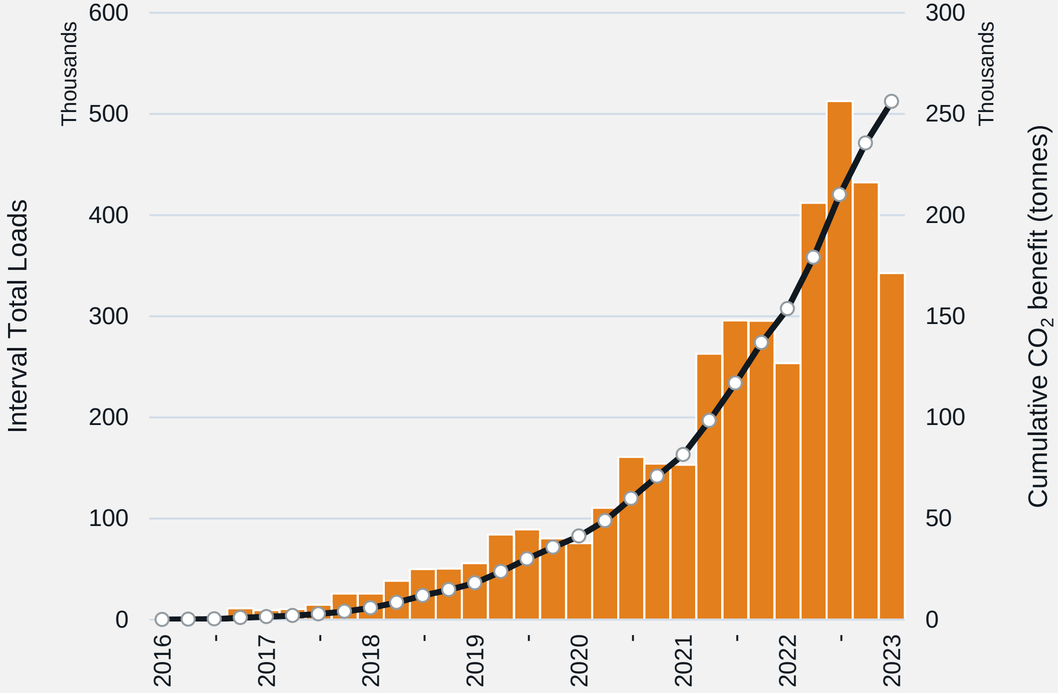
More than
700 systems across 30+ countries

Used to produce
30M+ yd^3 of concrete

Resulting in
250,000+ metric tons of CO_2 saved



Scalable Sustainability



4,011,983

Truckloads delivered with CarbonCure concrete

256,027.6

metric tons

Total CO_2 emissions saved with CarbonCure

Further reading

Performance, Durability, and Life Cycle Impacts of Concrete Produced with CO_2 as Admixture
ACIMatJ (2023) doi:10.14359/51734732

Early age impacts of CO2 activation on the tricalcium silicate and cement systems
JCOU 65 (2022) doi:10.1016/j.jcou.2022.102254.

Comparing the effects of in-situ nano-calcite development and ex-situ nano-calcite addition on cement hydration
CBM 321 (2022) doi:10.1016/j.conbuildmat.2022.126369

The impacts of in-situ carbonate seeding on the early hydration of tricalcium silicate
CCR 136 (2020) doi:10.1016/j.cemconres.2020.106179

Activation of cement hydration with carbon dioxide
JSCBM 7 (2018) doi:10.1080/21650373.2018.1443854

On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete
JCP 167 (2017) doi:10.1016/j.jclepro.2017.08.194

Properties and durability of concrete produced using CO_2 as an accelerating admixture
CCC 74 (2016) doi:10.1016/j.cemconcomp.2016.10.007

Thank You

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