Unlocking Concrete's Green Potential: Integrating Supplementary Cementitious Materials with Biomolecule-regulated Carbonation

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Problem Statement

Cement industry is one of the contributors to global CO_2 emissions

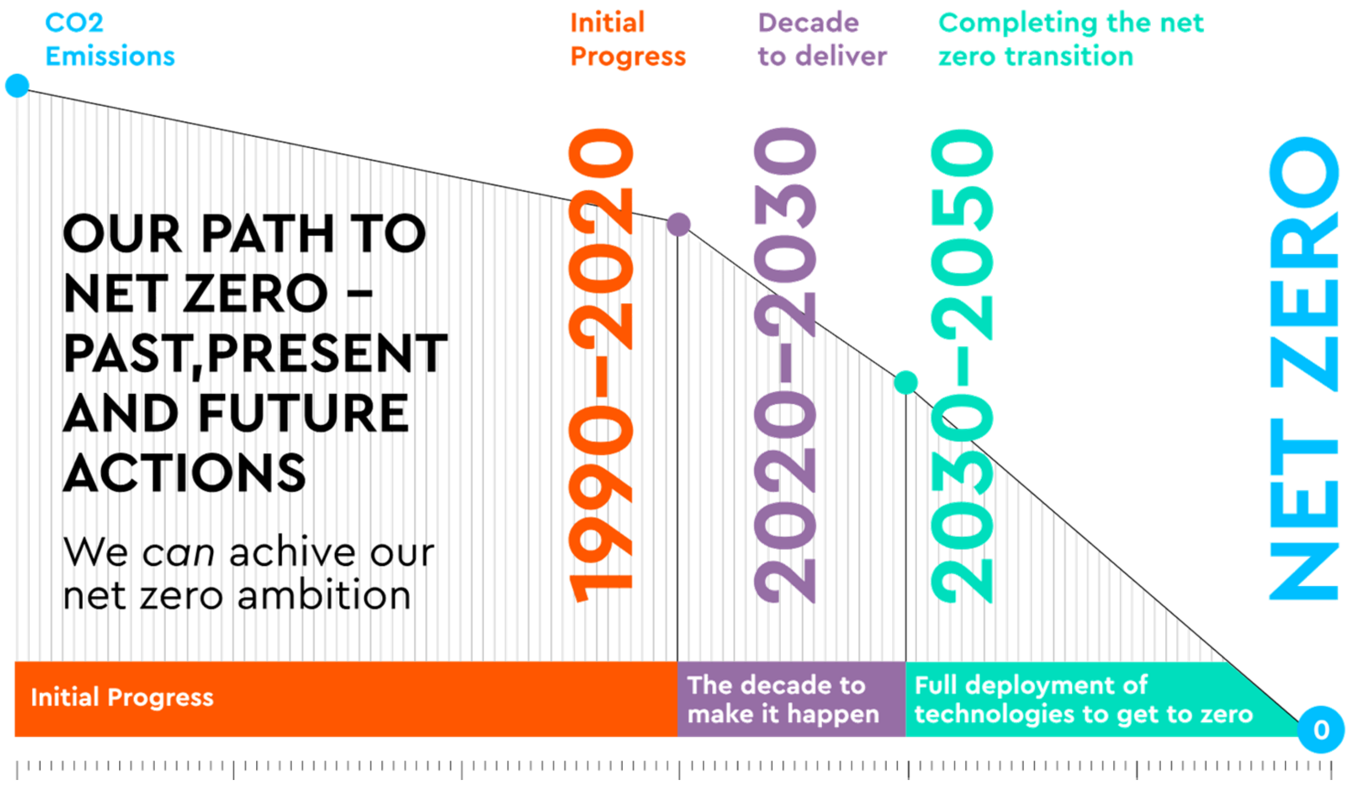


Image from Global Cement and Concrete Association (GCCA) roadmap to net-zero

Deep decarbonization:

→ Compatibility of methods

→ Quick implementation

→ Improved performance

Supplementary Cementitious Materials (SCMs)

→ Currently most adopted solution towards low-carbon concrete

→ SCMs are siliceous-aluminous materials commonly used as a partial replacement for cement

Cement hydration: $C_3S + H_2O \rightarrow C\text{-}S\text{-}H + \mathbf{CH}$

Pozzolanic reaction: $\mathbf{CH} + SiO_2 + H_2O \rightarrow C\text{-}S\text{-}H$

→ Latent property causes **low early-age strength** and **delayed setting time**

Limestone Calcined Clay Cement – LC^3

→ Due to the widespread availability of clay, LC^3 has become a popular ternary cement

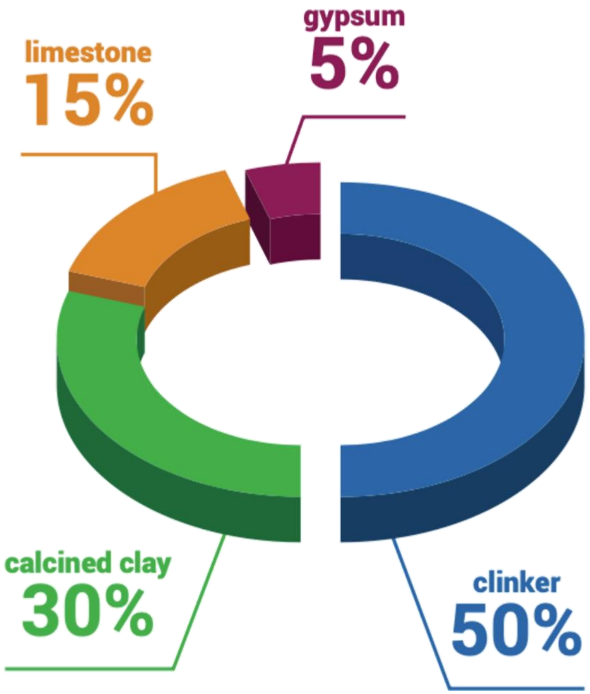
→ Synergy between alumina from calcined clay and carbonates from limestone

→ Stabilization of ettringite (AFt)

Alumina + gypsum + water → ettringite (AFt)

→ Formation of hemi- and monocarbonate (Hc and Mc)

Alumina + limestone + water → hemi- and monocarbonate



Utilizing CO_2 in Concretes

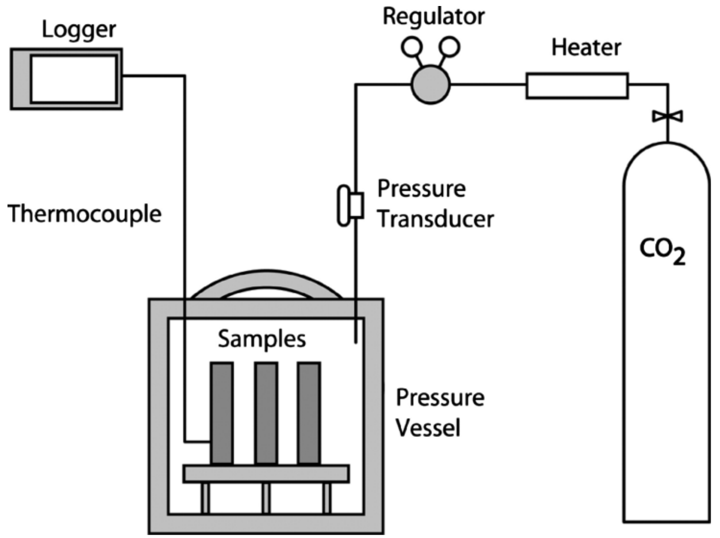
Carbonation Curing

Replacing water/steam with purified CO_2 for curing **after** concrete mixing

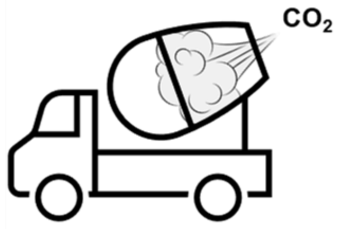
Improved strength at early-age

Limited applicability

→ Small members like concrete blocks
→ Precast (chamber required)



Utilizing CO_2 in Concretes



Mixing Carbonation

- Injecting purified CO_2 **during** concrete mixing

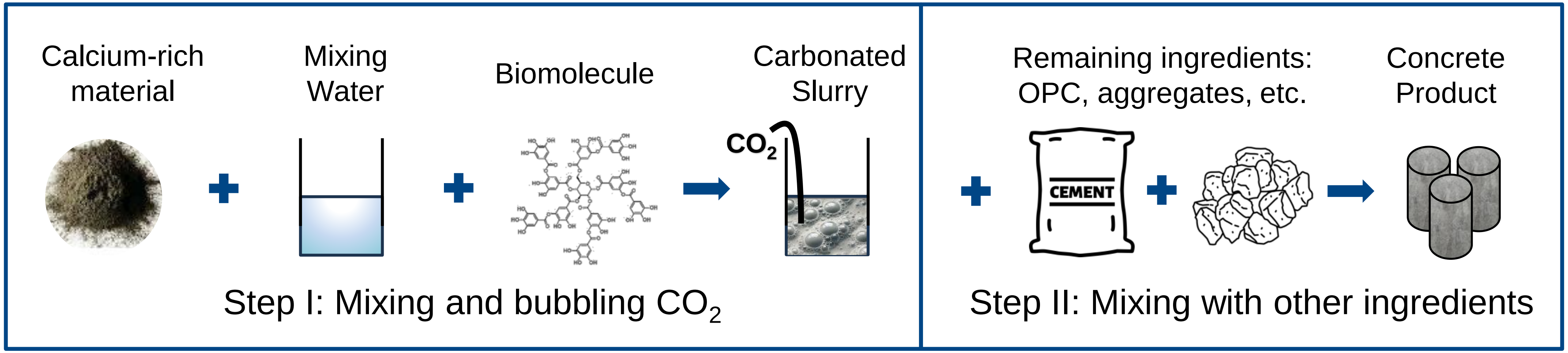
Precast and ready mix

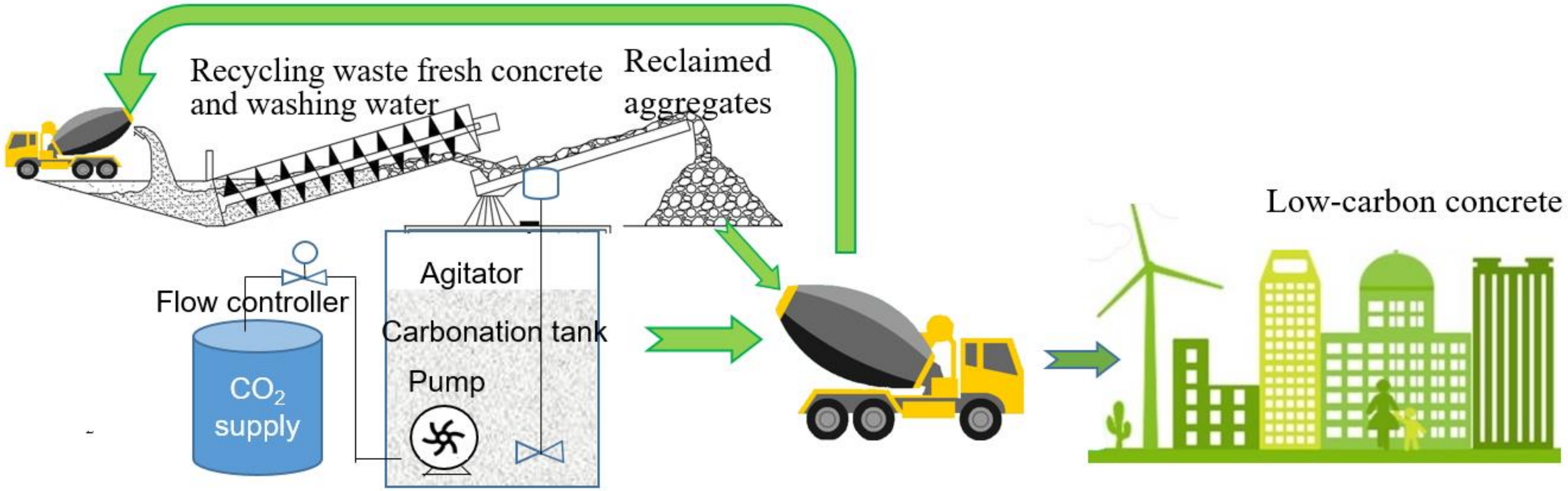
Strength improvement
(5 – 8% cement saved)

Some CO_2 released back to air

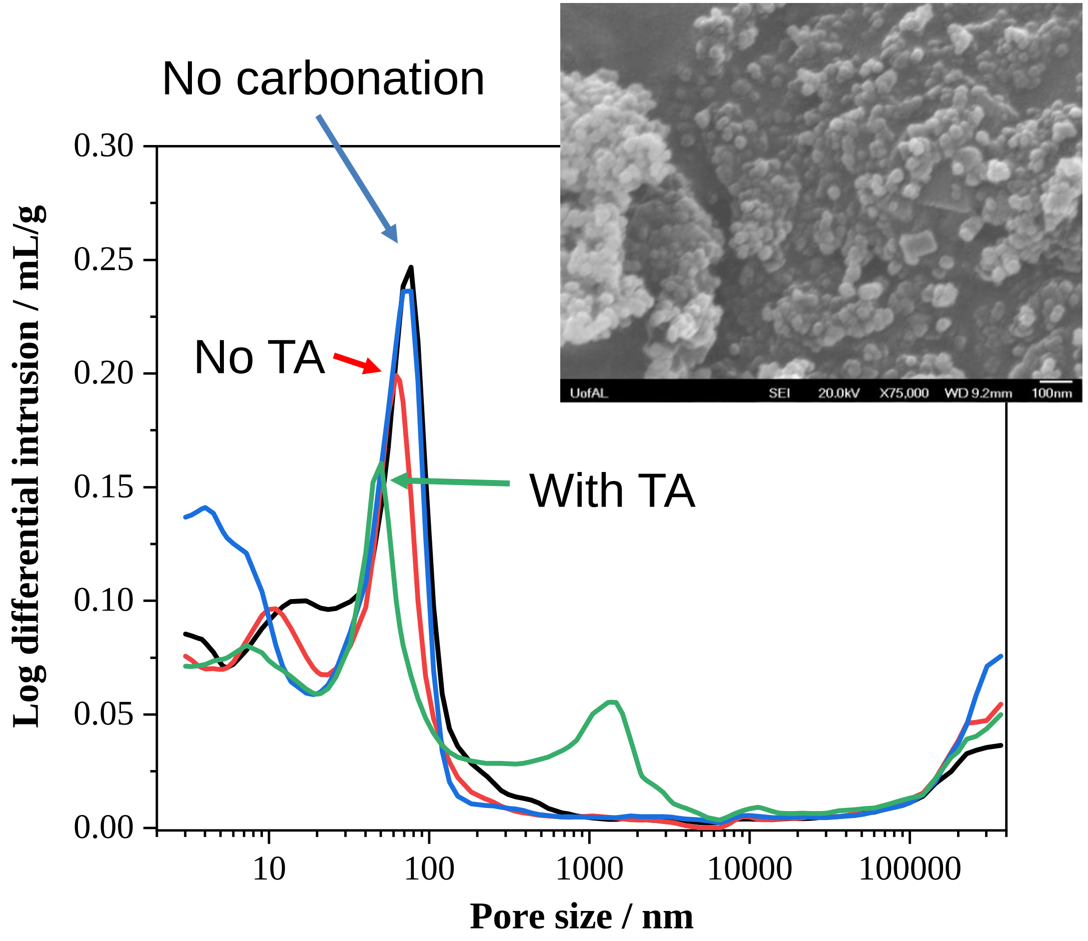
0.15 – 0.2% wt. of
cement in CO_2 storage

New Pathway: The BioCarb Method





BioCarb Method: How does it work?



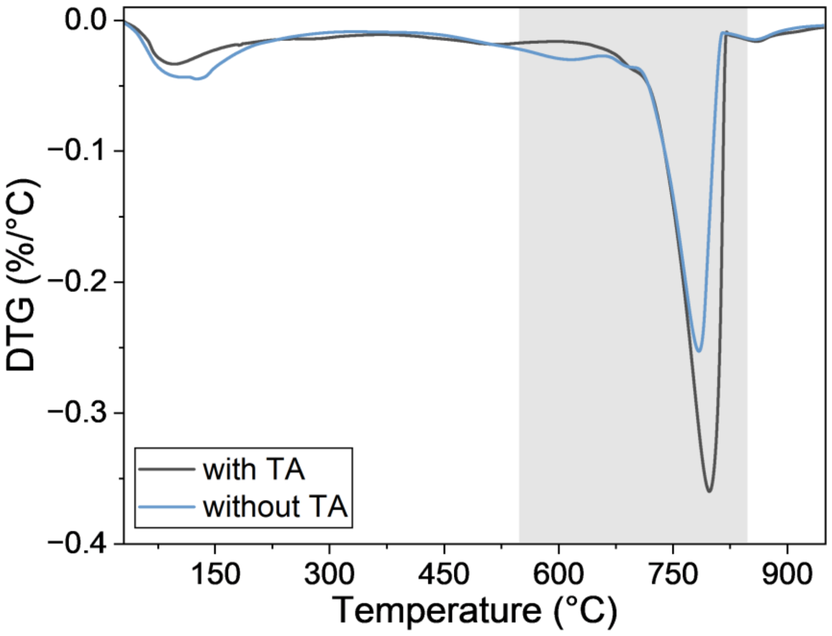
NanoCaCO$_3$ is produced in-situ

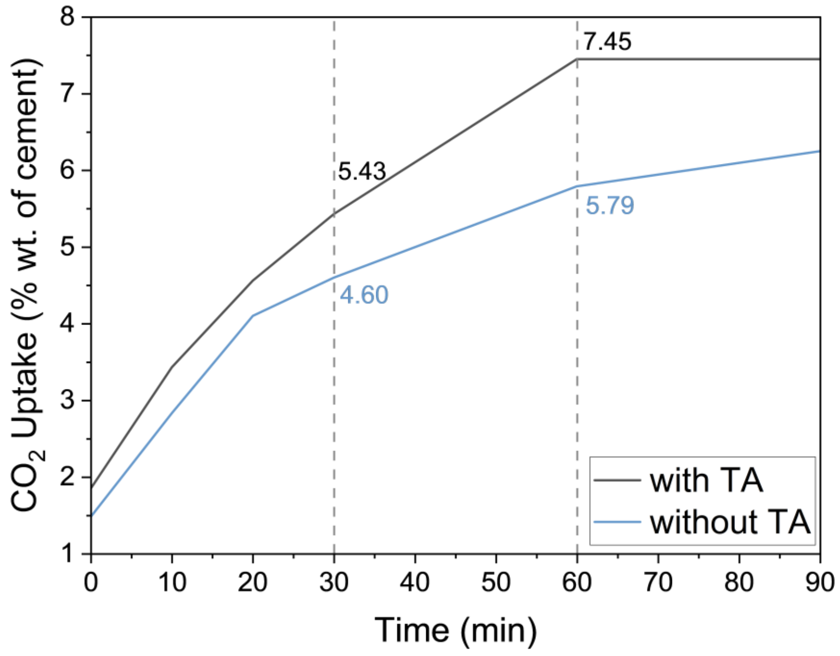
- Filler effect
- Seeding effect

Multi-functional biomolecule

- Regulate the crystal nucleation, orientation, size, and phase
- Disperse the produced CaCO$_3$ nanoparticles

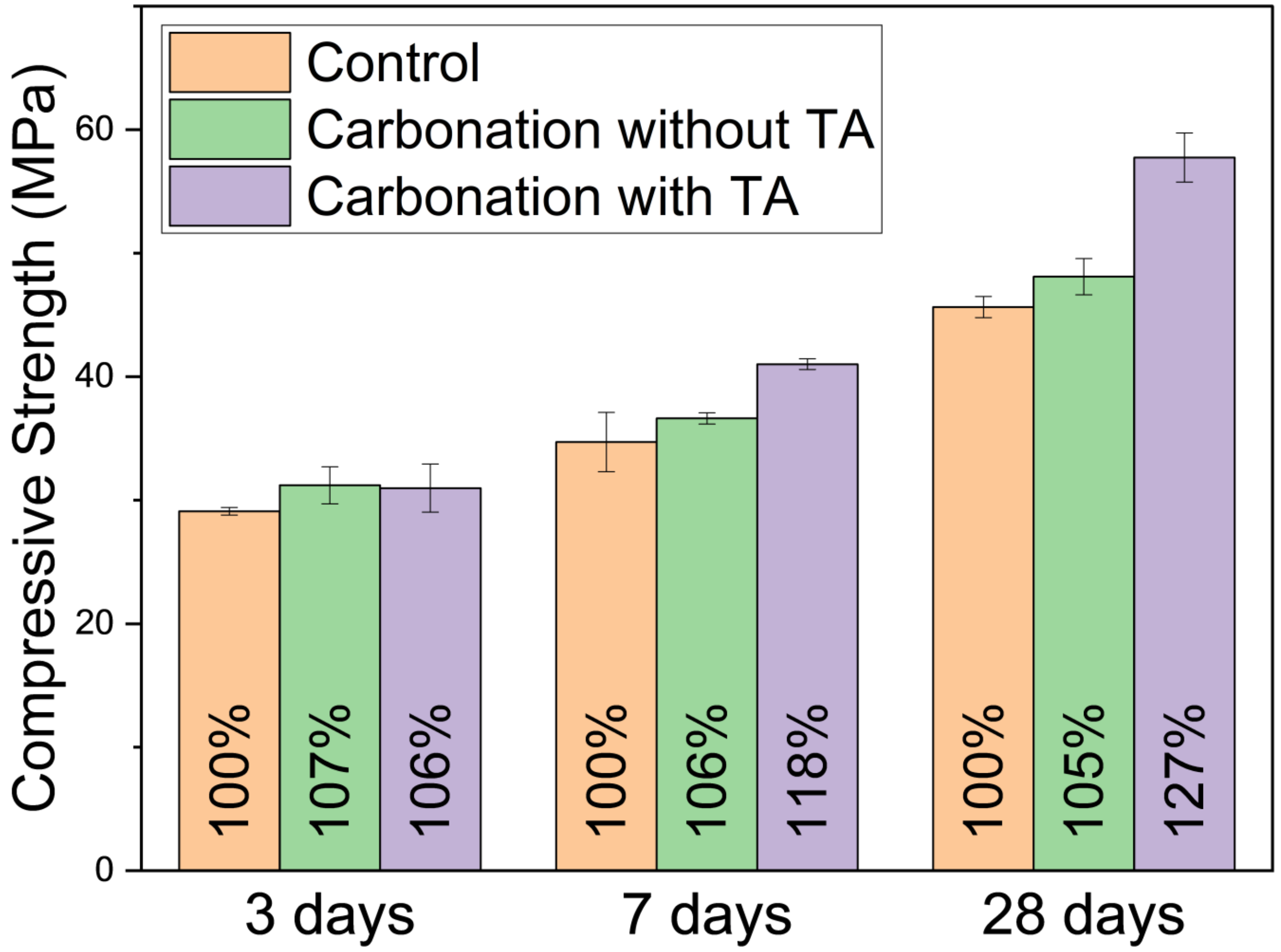
CO_2 Uptake





- CO_2 Uptake after 60 min = 7.45% (**30x better** than the existing technology)
- Carbonation duration depends on the added biomolecule
  - 30 – 60 min is sufficient for most applications

Strength Improvement



Water : Cement : Sand = 1:2:5

Production: half of cement mixed with all mixing water and carbonated with a biomolecule as a small dose additive

Over 25% strength improvement

Over 20% reduction on carbon intensity

Experimental Plan

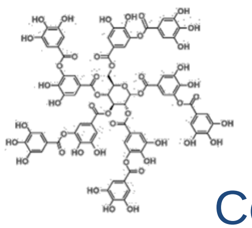
→ Portland cement was used as the calcium source in the slurry

→ Three SCMs were considered: class F fly ash, slag, and metakaolin

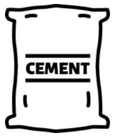
→ Two main factors were analyzed

1. Tannic Acid concentration
2. Carbonation time

xT yPC zmC



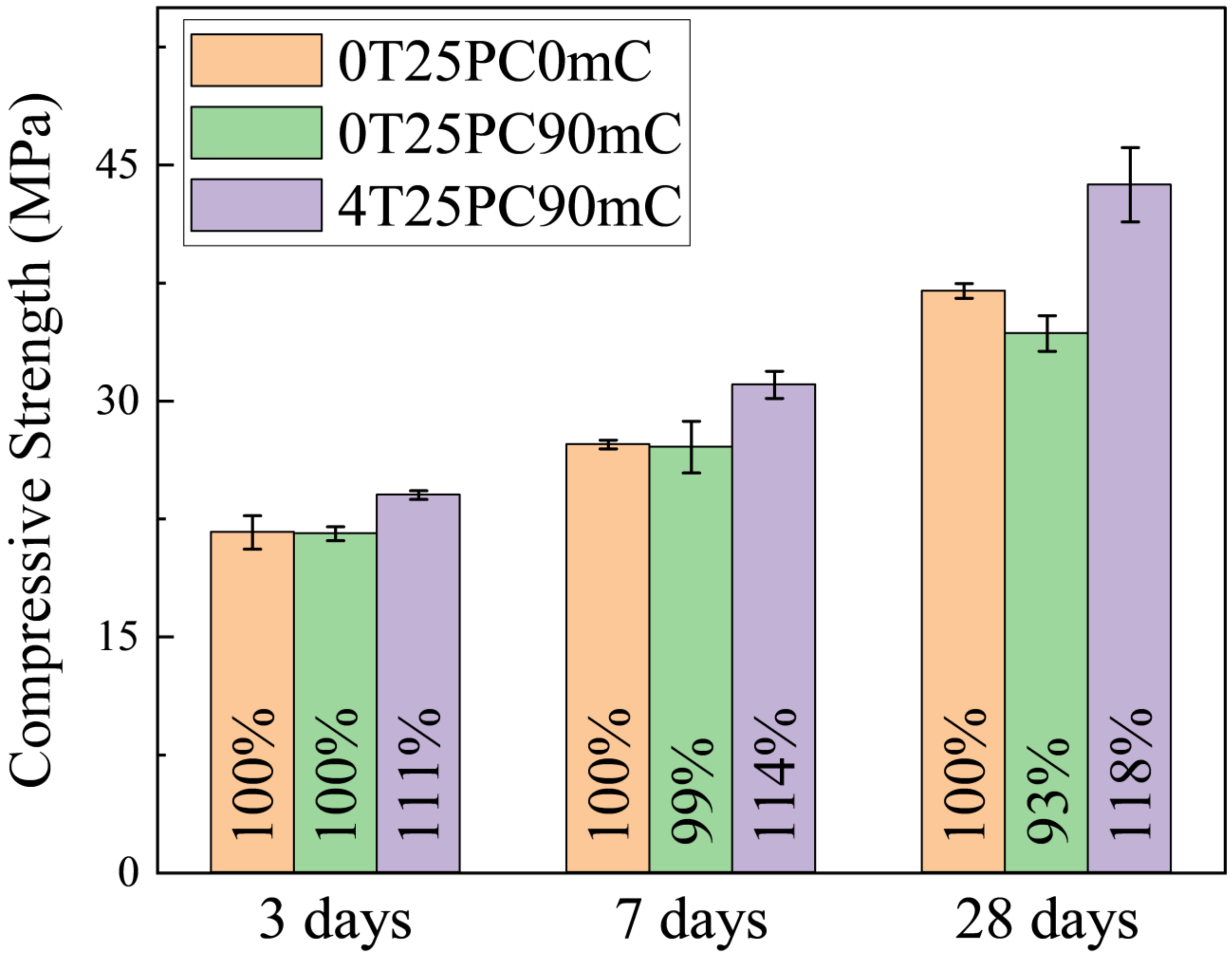
Tannic Concentration



Portland Cement Concentration

Carbonation time in minutes

Compatibility with Fly Ash



→ Replacement of **20% of cement**

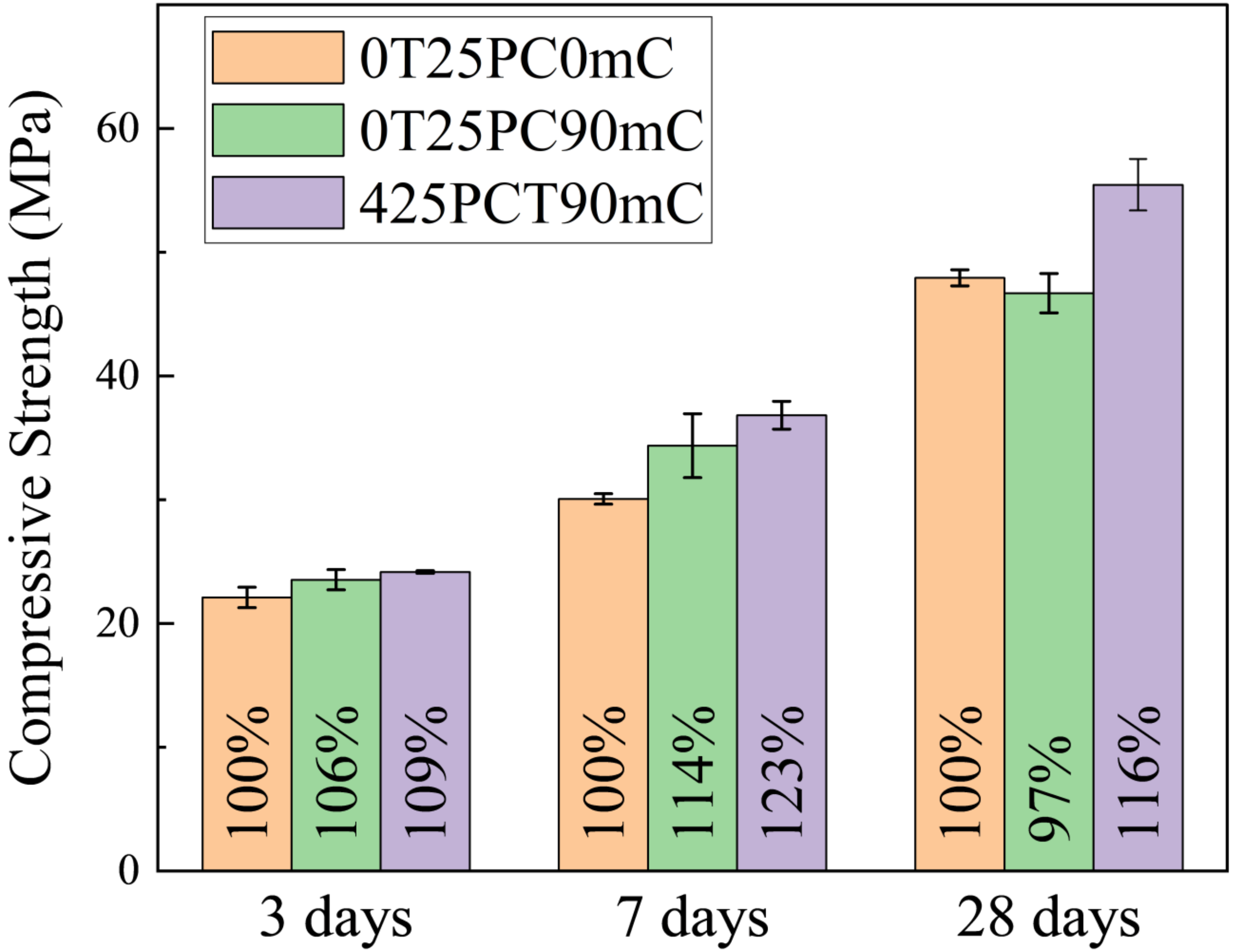
→ 25% of cement in the slurry

→ Class F fly ash

→ Early age improvement

→ No compromise to late age strength

Compatibility with Slag

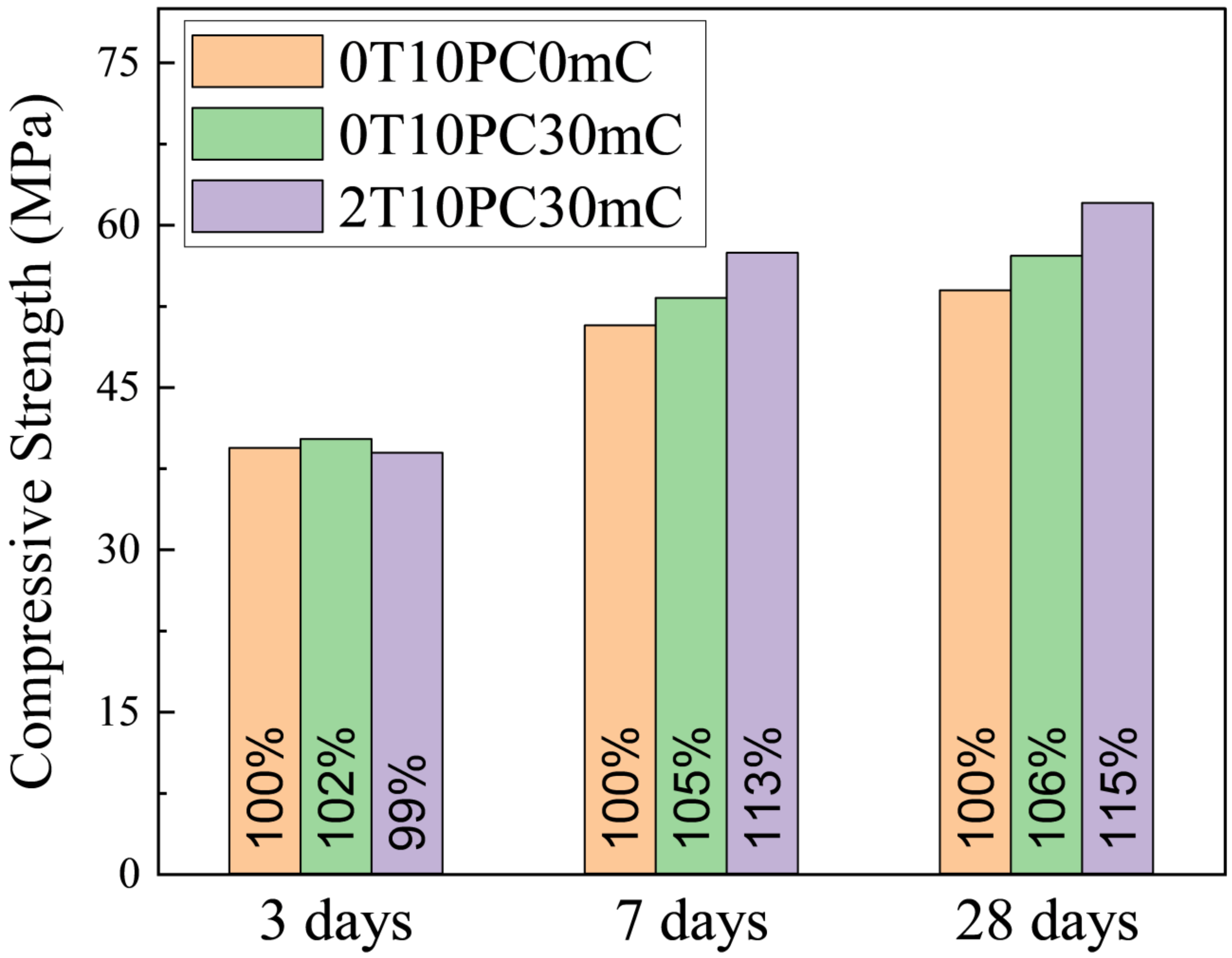


→ Replacement of **30% of cement**

→ 25% of cement in the slurry

→ Improved performance at all ages

Compatibility with Metakaolin



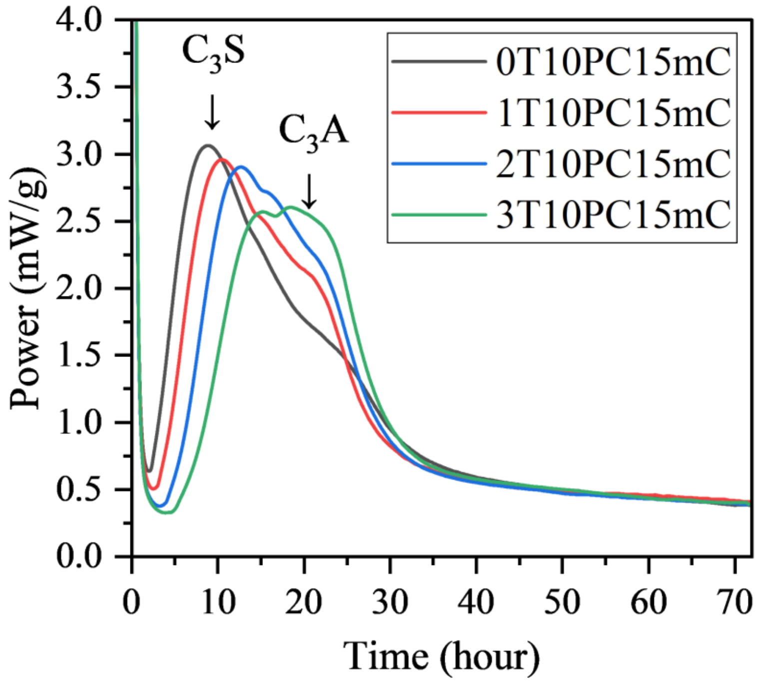
→ **Replacement of 20% of cement**

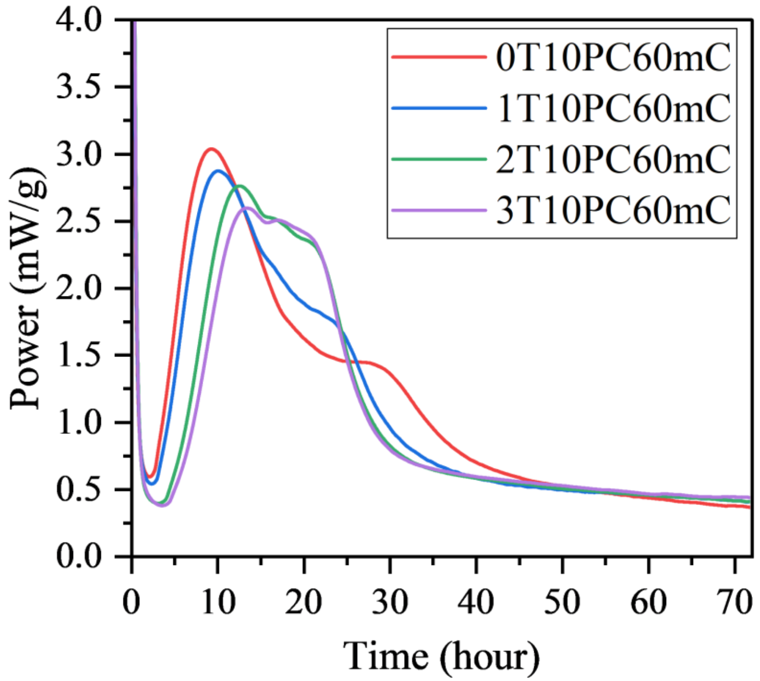
→ 10% of cement in the slurry

→ 30 minutes of injection

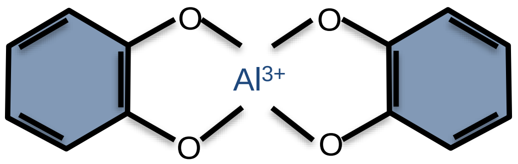
Hydration Kinetics

→ Synergy between alumina and tannic acid



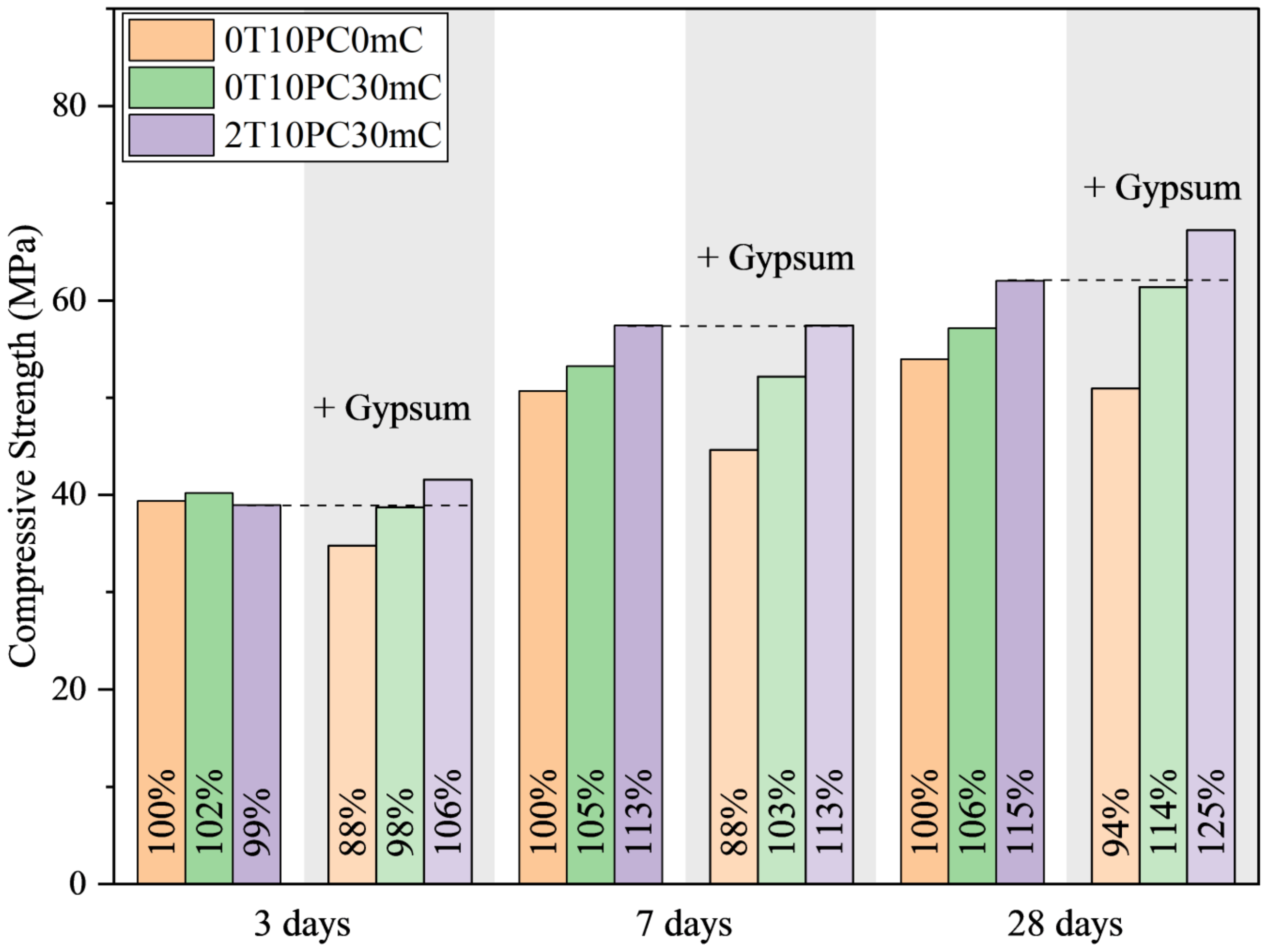


Metal-polyphenol coordination



Promotion of C_3A reactivity

Gypsum Adjustment



→ Recovery on 3 days strength

→ 1.5% gypsum addition

→ 28 days strength improved an extra 10%

Conclusions

1. BioCarb method shows compatibility with all traditional SCMs
2. Compound environmental impact:

→ Reutilization of waste wash-water (5 – 25% of cement recycled in the water)

→ Improved CO_2 storage (almost 8% uptake)

→ Improved mechanical performance (25% increase in strength)

→ Partial replacement of cement (20 – 30% of SCMs usage)

Thank you!

NSF's Convergence Accelerator

U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

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