# MECHANISTIC INSIGHTS INTO LONG-TERM INTEGRITY OF CEMENT AND STEEL-CEMENT INTERFACE IN $CO_2$ STORAGE FACILITIES

12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION

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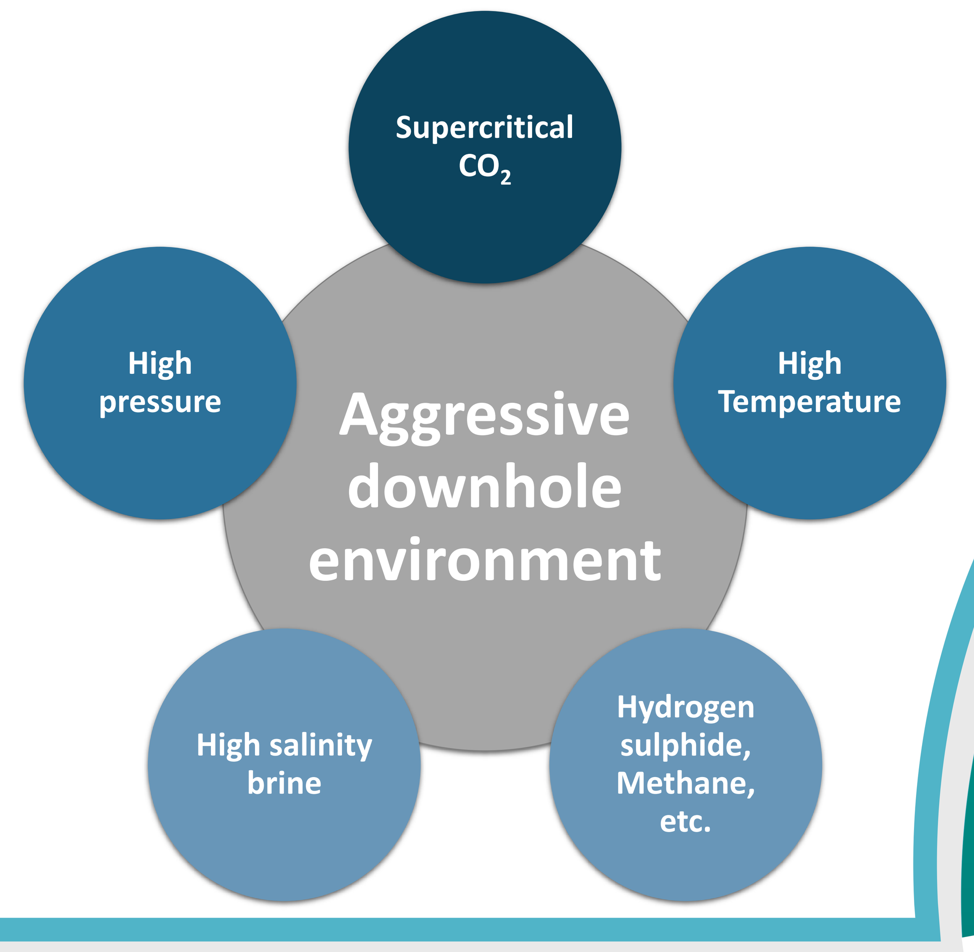
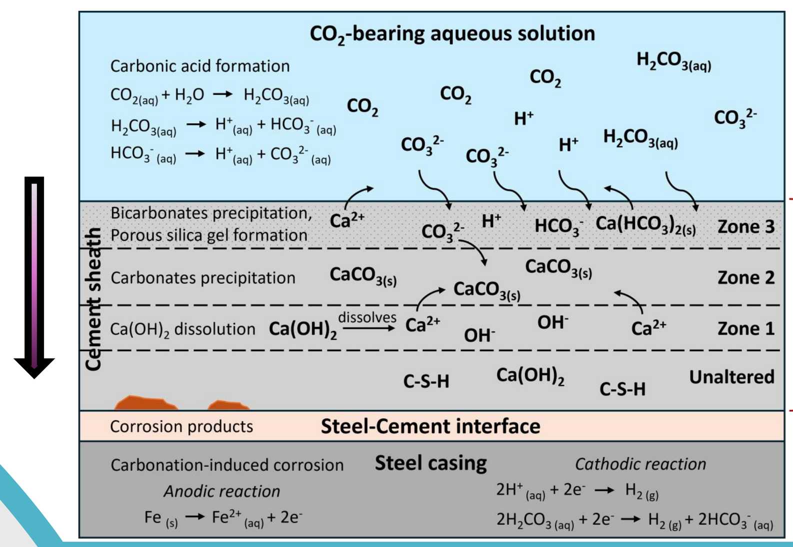
## Background

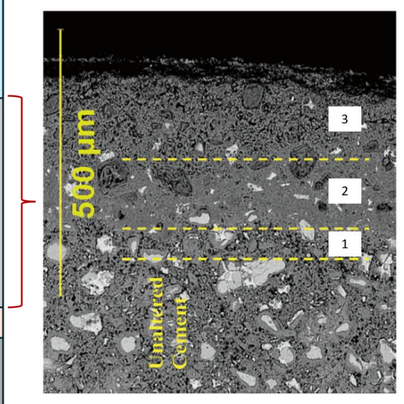
- **Long-term wellbore integrity** with low risk of carbon dioxide ($CO_2$) leakage is the key to safe and effective $CO_2$ storage
- **$CO_2$ leakage through steel-cement (S-C) system** is reported to occur much more rapidly than geological leakage through formation rock in a $CO_2$ storage reservoir [1]
- Exposure of cement to $sCO_2$ or $CO_2$-bearing brines may lead to **carbonation of cement**, potentially causing **cement degradation** and **corrosion of steel**

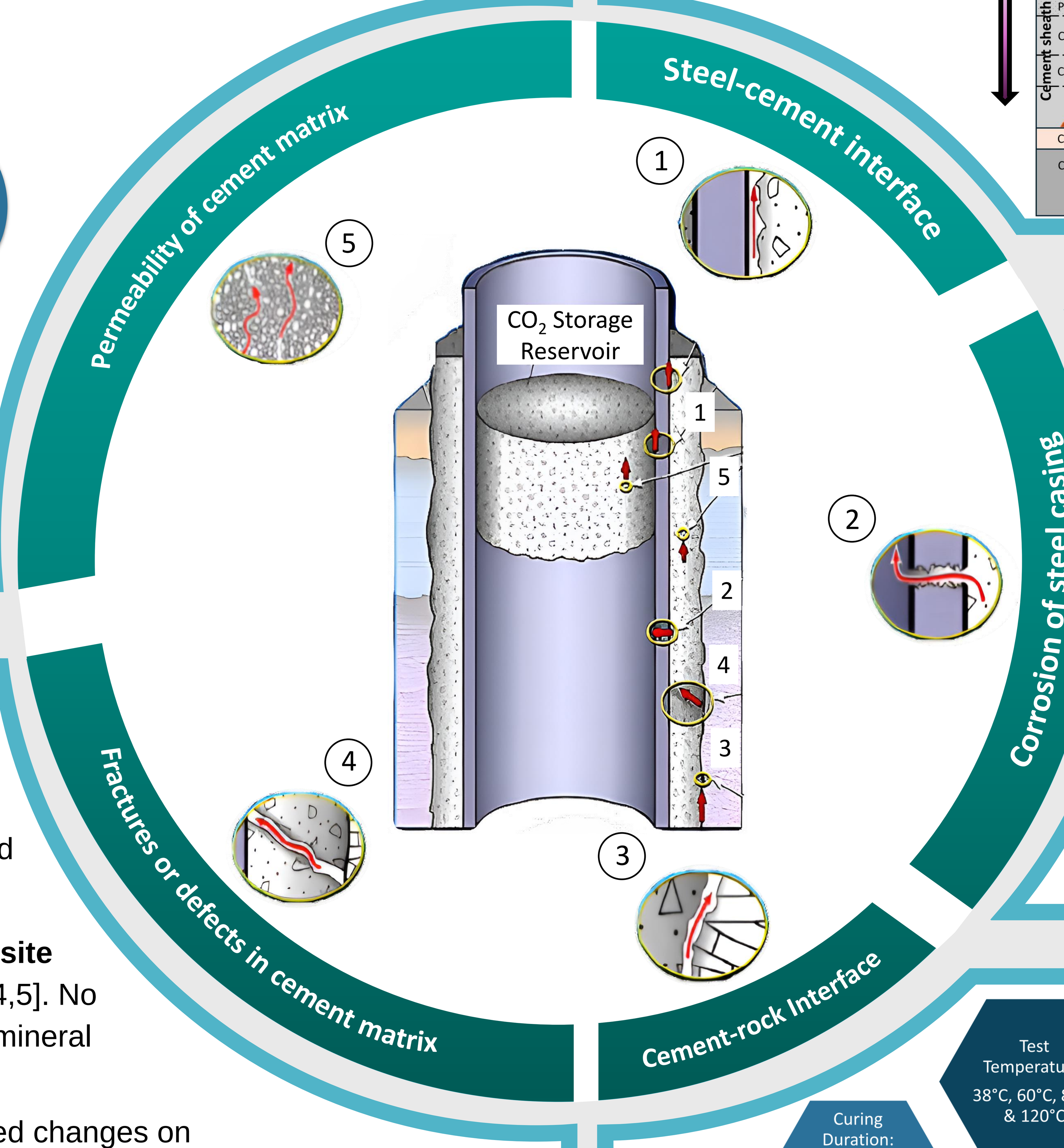



## Degradation Mechanism

- Initially calcium carbonate precipitation may lead to **pore refinement** and improved mechanical strength
- **Over extended exposure**, due to calcium leaching and C-S-H dissolution, **porosity increases**, and **strength reduces**
- Thermodynamic end state of carbonated cement slurry is an assemblage of **calcium carbonate, gypsum** and **oxide/ hydroxides of silica, alumina and iron**




## Aim & Objectives

Effect of **water-saturated $sCO_2$ & $sCO_2$-saturated brine** on integrity of cement and S-C interface at simulated wellbore conditions

**1 Critical Curing conditions**
- Degree of hydration and hydration kinetics
- Phase assemblage
- Mechanical strength

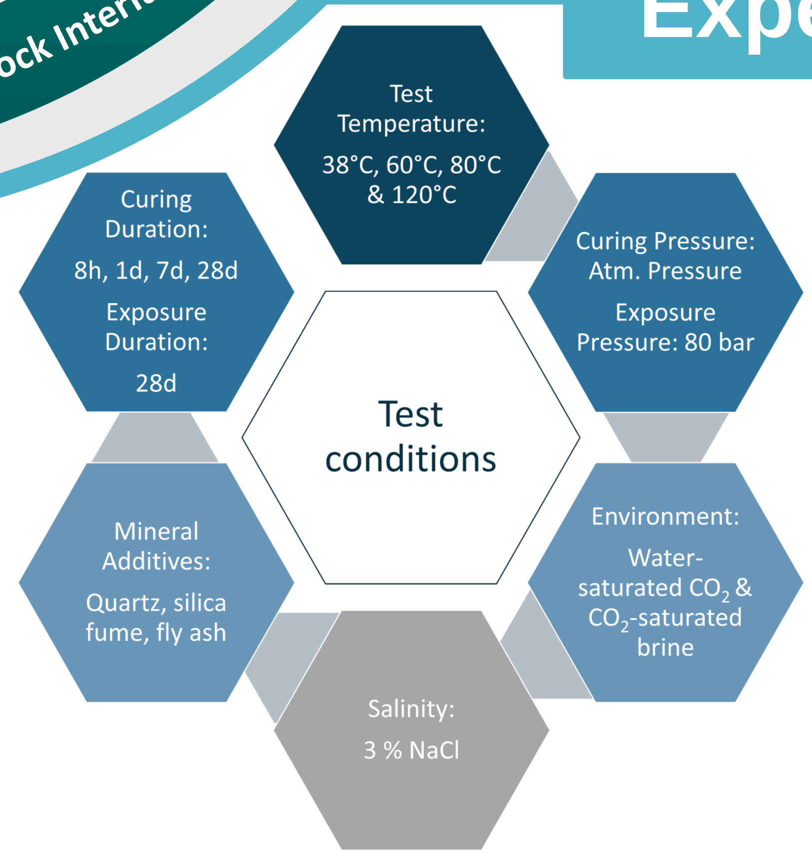
**2 Cement-Environment interaction**
- Physico-chemical changes
- Mechanical strength
- Durability properties

**3 Integrity of S-C interface**
- Corrosion performance in simulated conditions
- Physical and chemical characteristics at the S-C interface
- Bond strength at interface after 6 months of steel corrosion

## Research Gaps

- Limited understanding of the effect of **high temperature (HT) & high pressure (HP) curing for longer duration** on hydration and carbonation kinetics of well cements
- Contradictory findings on the **use of composite cements** to improve long-term durability [3,4,5]. No clear agreement on the practical dosage of mineral additives
- No clarity on the effect of carbonation-induced changes on **permeability and strength of cement**
- Lack of **representative test methodology** to characterise durability performance and its relationship to long-term durability

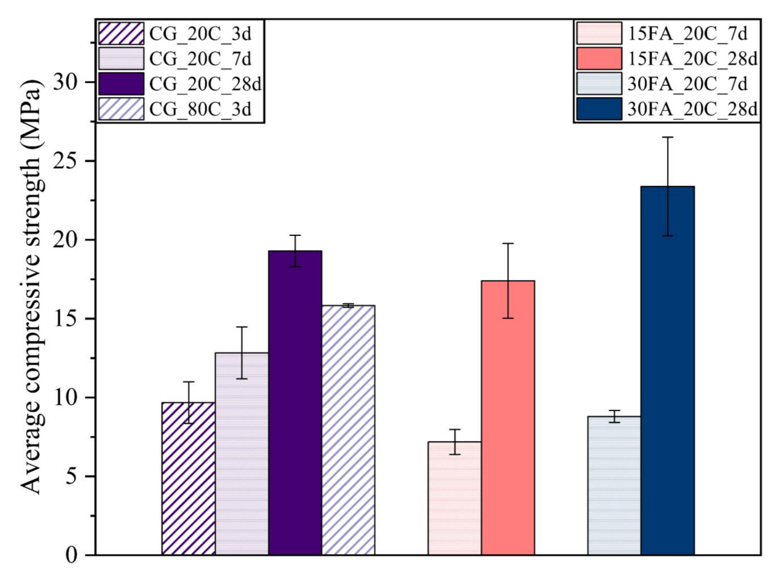
## Experimental Plan



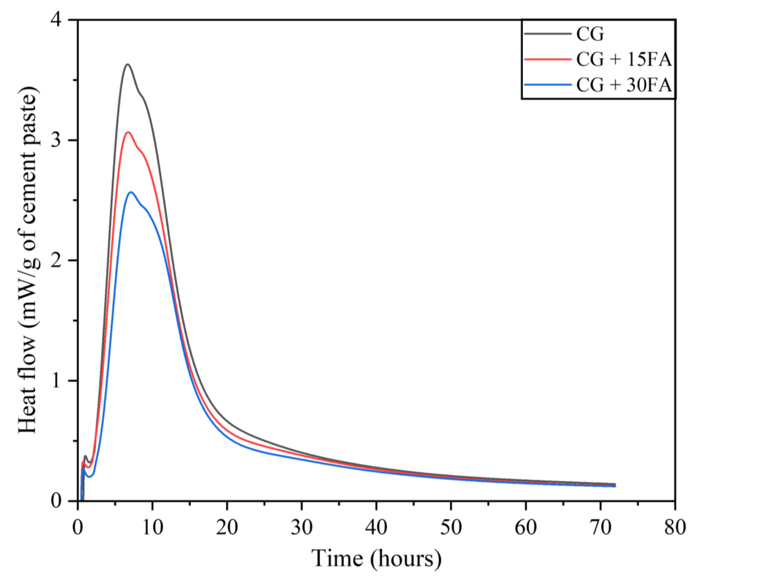

**Autoclave for tests in simulated well conditions**

| Hydration & phase assemblage | Mechanical properties | Transport & durability properties | Corrosion performance |
|---|---|---|---|
| • Evolution of hydration products at different curing ages (XRD, TGA)<br>• Hydration kinetics at different HT (Isothermal calorimetry)<br>• Carbonation reaction products | • Compressive strength at different curing ages and after carbonation<br>• Strength retrogression at HT (120°C) | • Porosity – before & after carbonation (SEM)<br>• Water Sorptivity<br>• Bulk resistivity<br>• Carbonation depth | • Electrochemical sensing technology using autoclaves<br>• Electrochemical Impedance Spectroscopy (EIS)<br>• Linear Polarisation resistance (LPR) |

## Preliminary Results




**Average compressive strength of cement samples cured at 20 °C and 80 °C for different ages**




**Heat flow curves of cement samples tested at 38 °C for 3 days in an Isothermal Calorimeter**

## Acknowledgements

The authors would like to acknowledge funding provided via the European Commission's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie Grant Agreement ID: 101118369, Material Science Innovation for Accelerated, Sustainable and Safe Implementation of Carbon Capture and Storage (MISSION-CCS)

MSCA

## References

[1] S.E. Gasda, S. Bachu, M.A. Celia (2004). "Spatial characterisation of the location of potentially leaky wells penetrating a deep saline aquifer in a mature sedimentary basin". Environmental Geology 46: p. 707-720
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[3] R.B. Pernites and A.K. Santra (2016), "Portland cement solutions for ultra-high temperature wellbore applications", Cement and Concrete Composites 72: p. 89-103
[4] J. Qin, X. Pang, G. Cheng, Y. Bu, H. Liu (2021), "Influences of different admixtures on the properties of oil well cement systems at HPHT conditions", Cement and concrete composites 123: p. 104202
[5] K. Abid, R. Gholami, P. Choate, B.H. Nagaratnam (2015), "A review on cement degradation under CO2-rich environment of sequestration projects", Journal of Natural Gas Science and Engineering 27: p. 1149-1157

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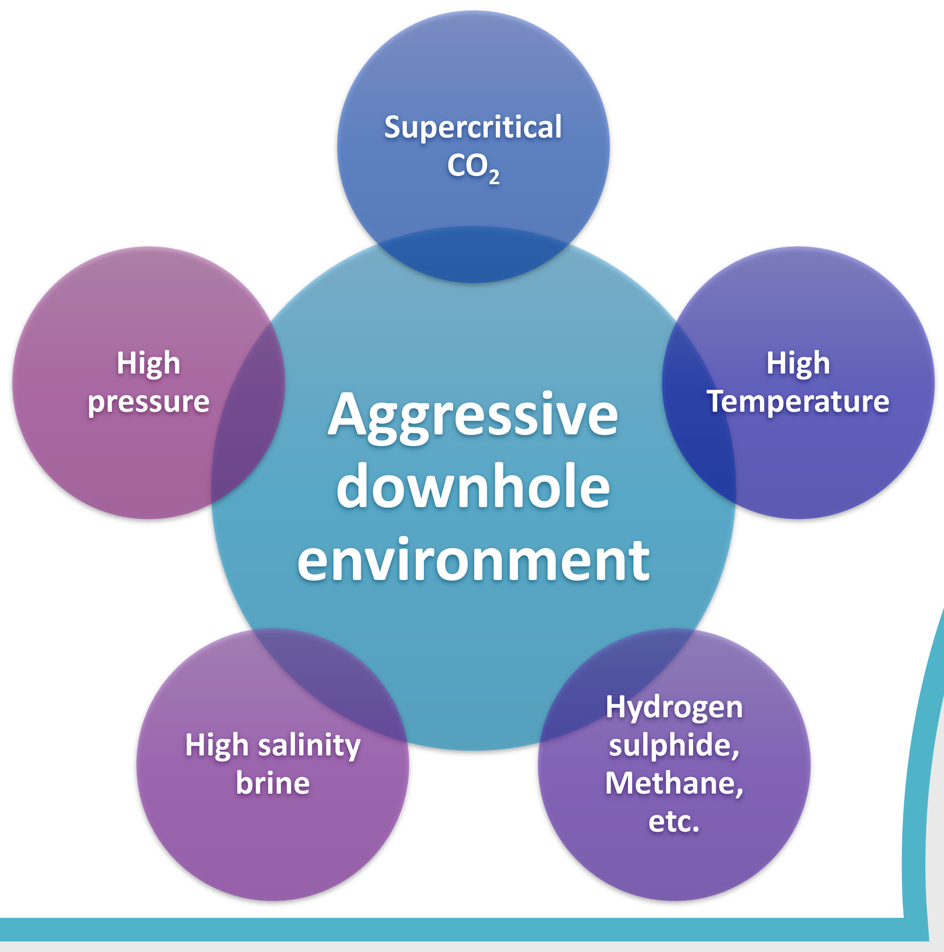
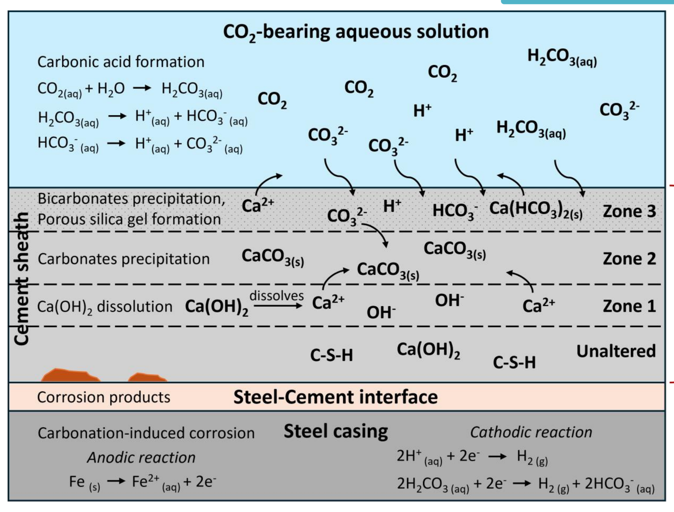
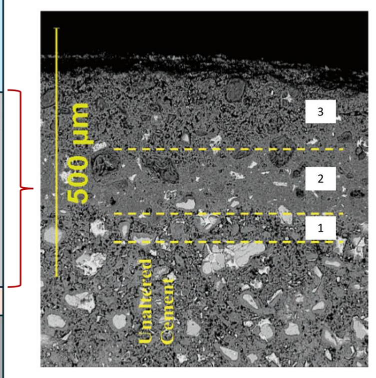
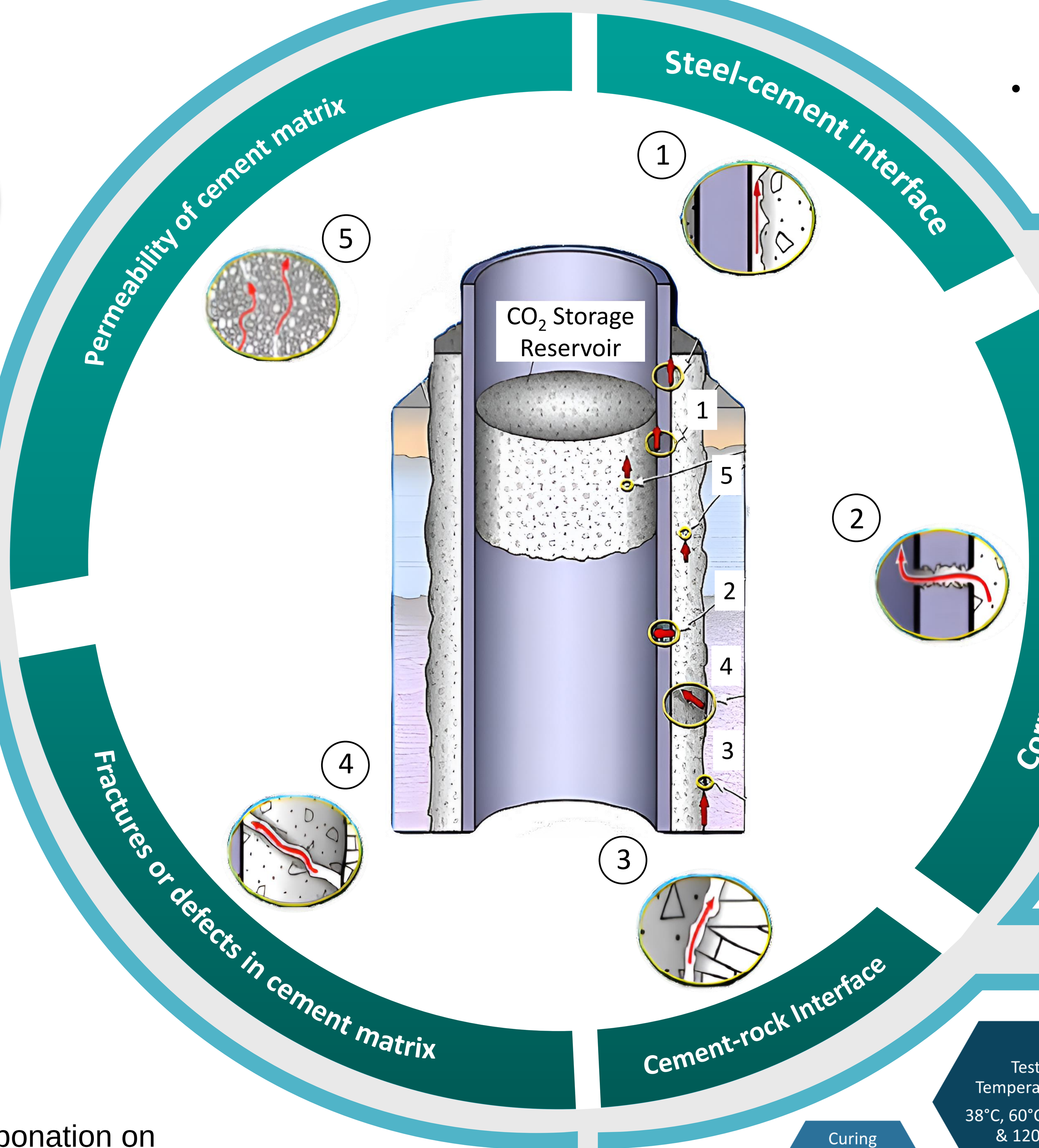



## Degradation Mechanism




- **At early stage**, calcium carbonate precipitation leads to **pore refinement** and improved mechanical strength
- **Over extended exposure**, due to calcium leaching and C-S-H dissolution, **porosity increases**, and **strength reduces**
- Thermodynamic end state of carbonated cement is an assemblage of **calcium carbonate** and **oxide/ hydroxides of silica, alumina and iron**




## Research Gaps

- Studies on effect of **high temperature (HT) & high pressure (HP) curing** on hydration and carbonation kinetics of well cements are contradictory
- Limited understanding on **use of composite cements** to improve long-term durability. No clear agreement on practical dosage of mineral additives.
- Contradictory conclusion on the effect of carbonation on **permeability and strength of cement**
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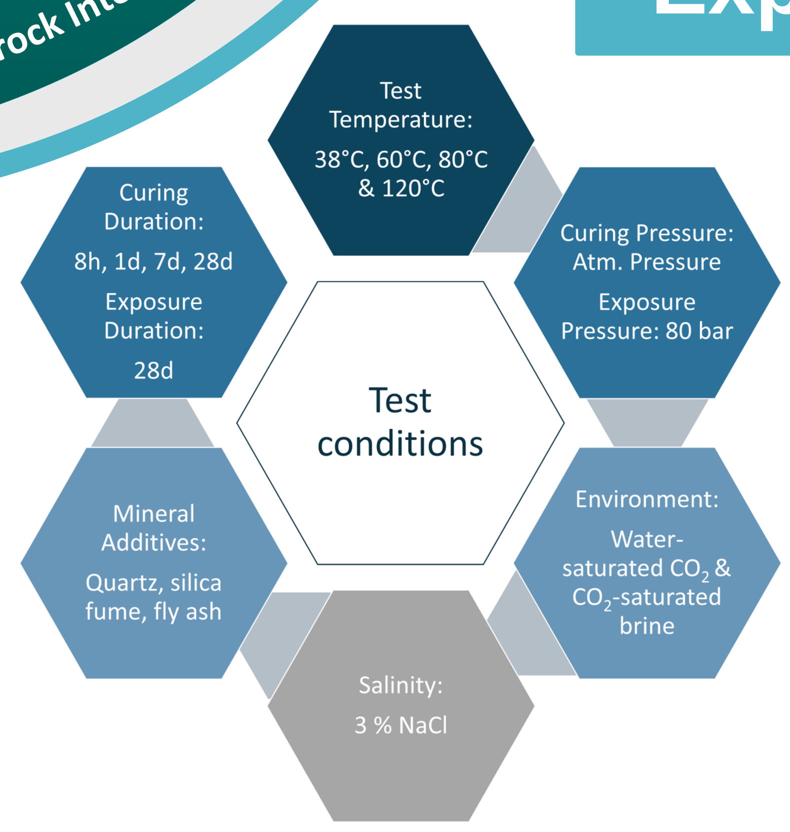


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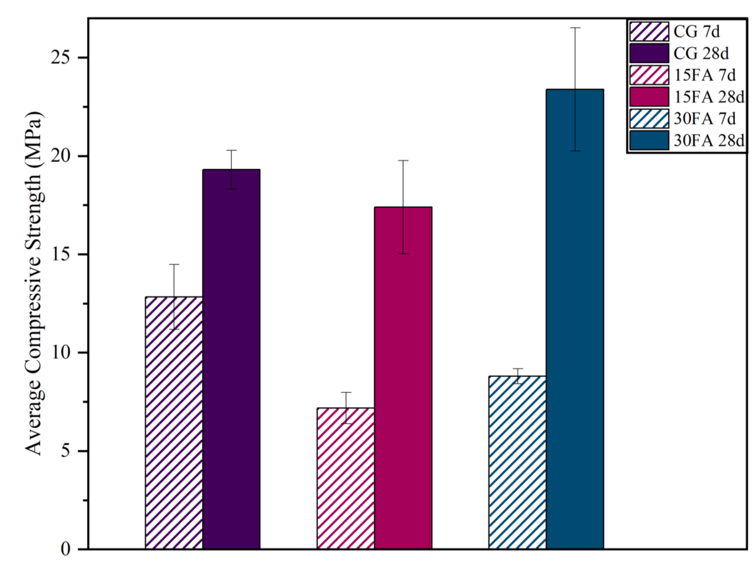
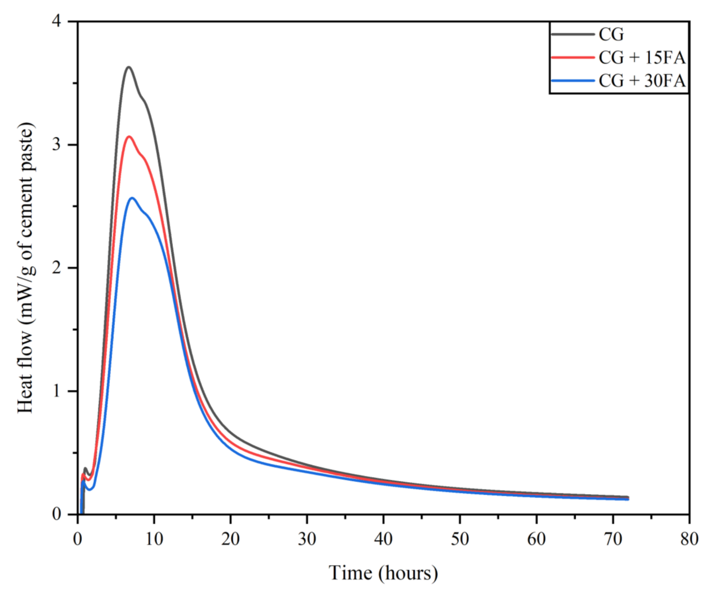
## Preliminary Results




Average compressive strength of cement samples cured at 20 °C for 7 days and 28 days




Heat flow curves of cement samples tested at 38 °C for 3 days in an Isothermal Calorimeter

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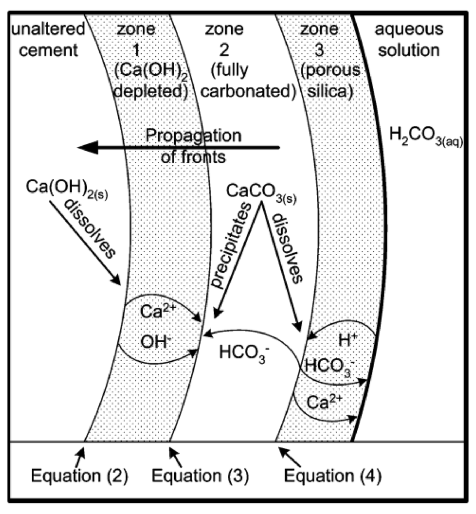
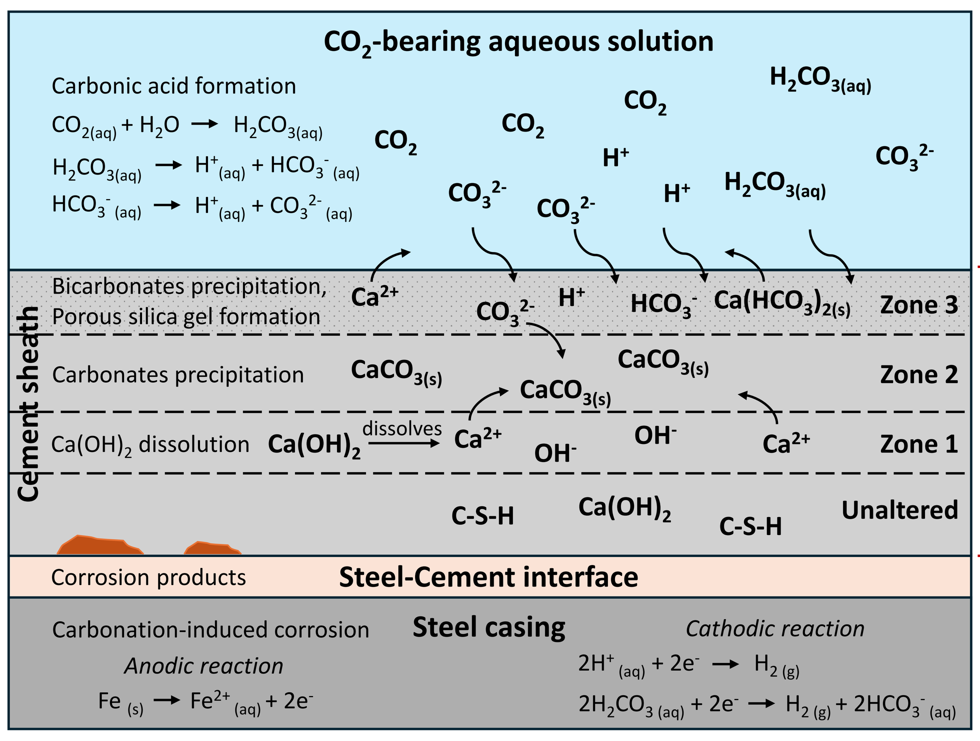
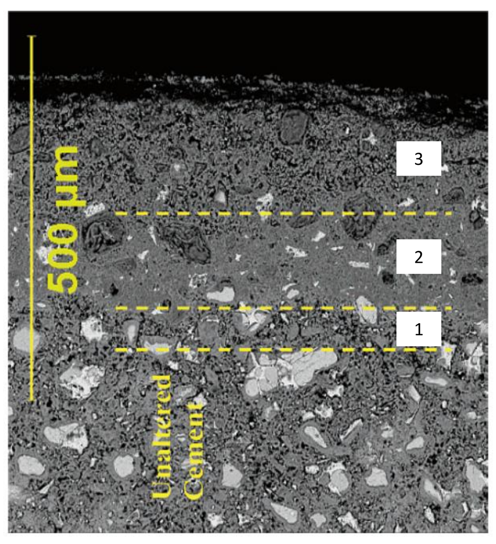



**FIGURE 3. Schematic showing the dissolution and calcium migration and formation of distinct zones in the cement. Equation numbers refer to chemical reactions that occur at each front as detailed in the text. Note: in the cement structure, local pH is buffered by $CaCO_{3(s)}$ and $Ca(OH)_{2(s)}$.**

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