

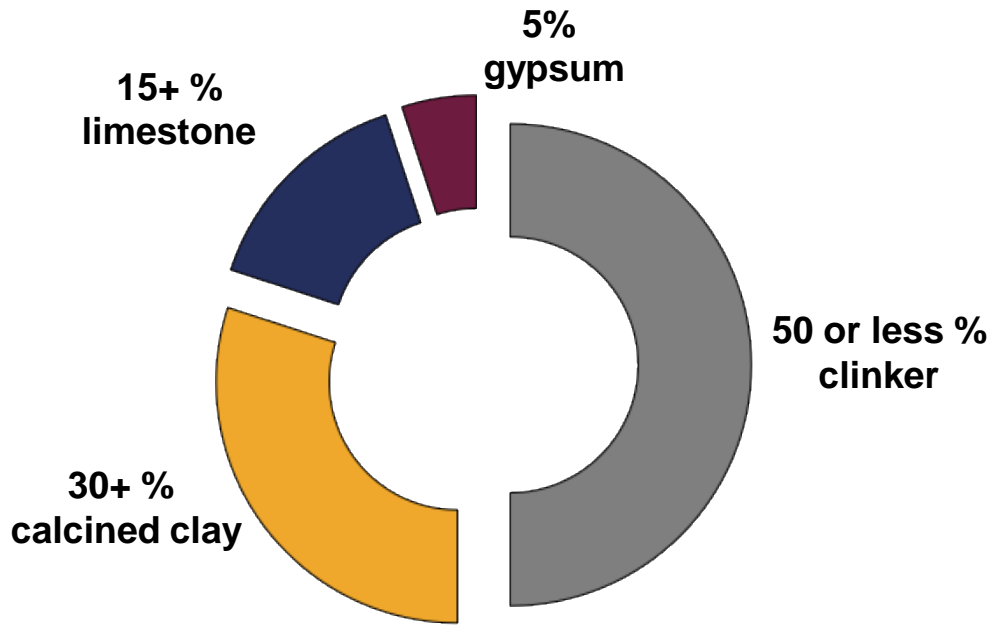
Carboaluminates: the overlooked key to high-performance LC³ cements

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What we have achieved with calcined clays



- ✓ 50% clinker
- ✓ 30-40% less CO₂ compared to PC
- ✓ Equivalent performance to PC
- ✓ Enhanced durability

CEM II/C-M (Q-LL) (*EN 197-5*)
CEM IT (P30)(L15) (*ASTM C595*)

Calcination

Kaolinite → Metakaolin



A: Al₂O₃
S: SiO₂
H: H₂O



- Reactive
- Abundant

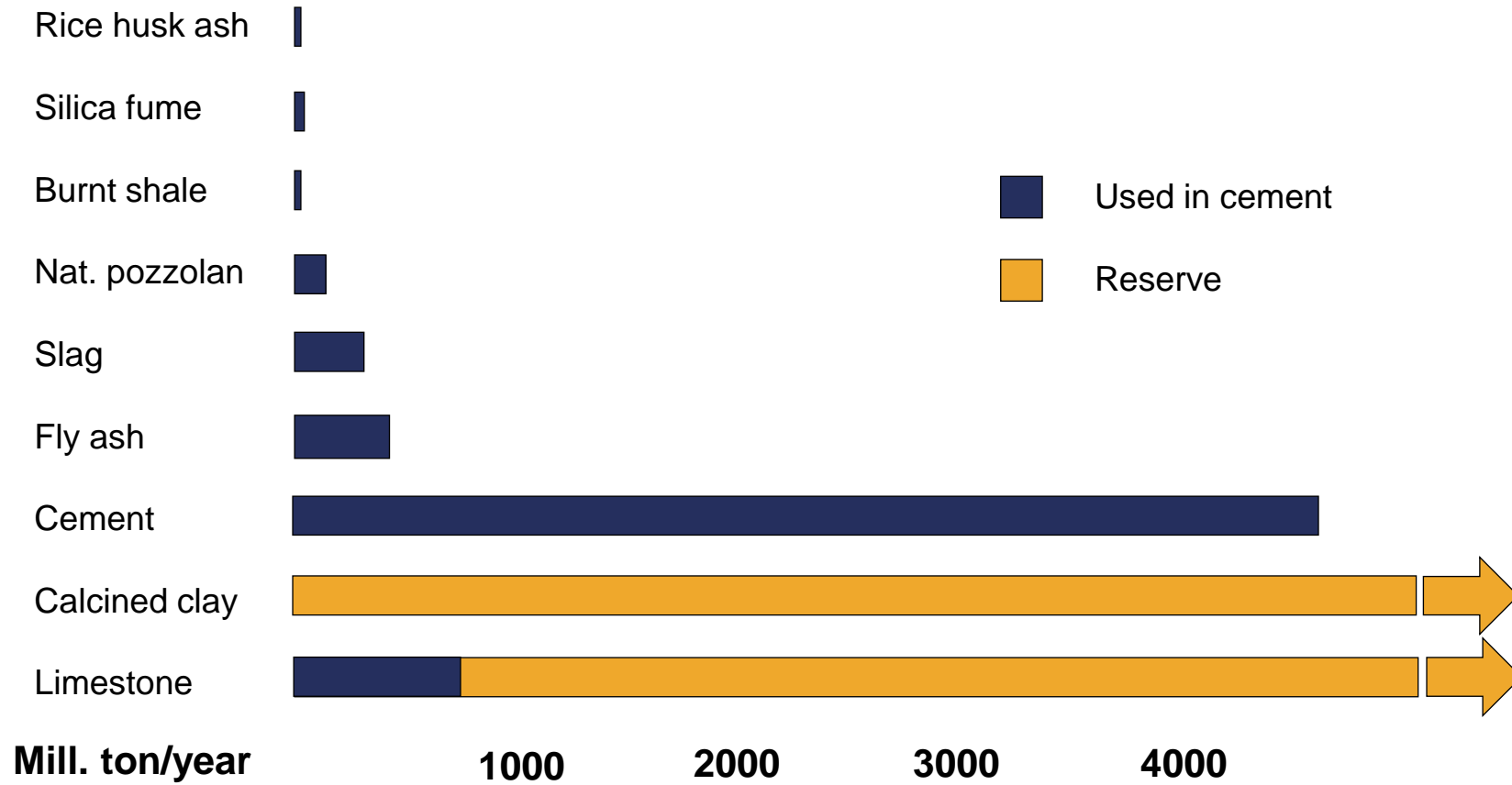
Metakaolin



First LC³ deployment in CA (National Cement)

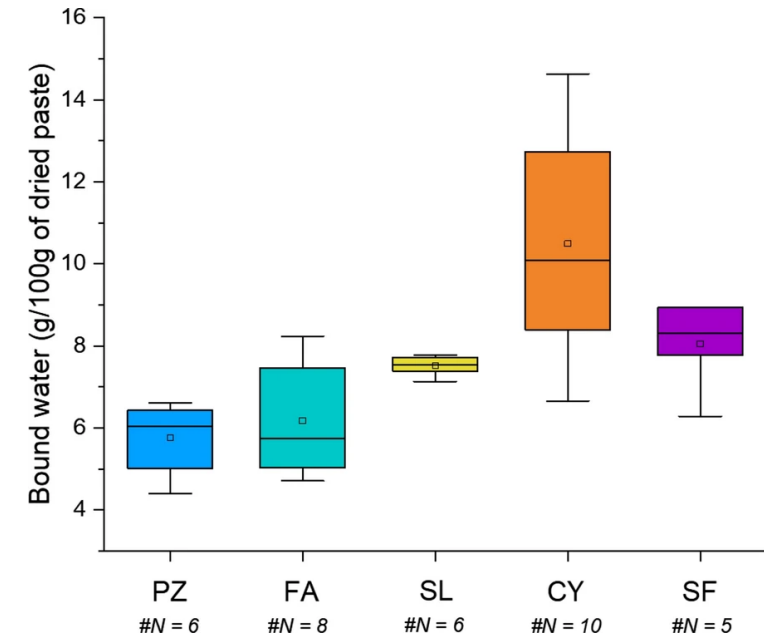
Replacing part of portland cement by **low-carbon materials** is the most effective **strategy to cut CO₂ emissions**

Availability argument



(UNEP, 2016)

Reactivity argument



Londono-Zuluaga et al., Mater. Str. 2022

Reactivity of calcined clays saves clinker

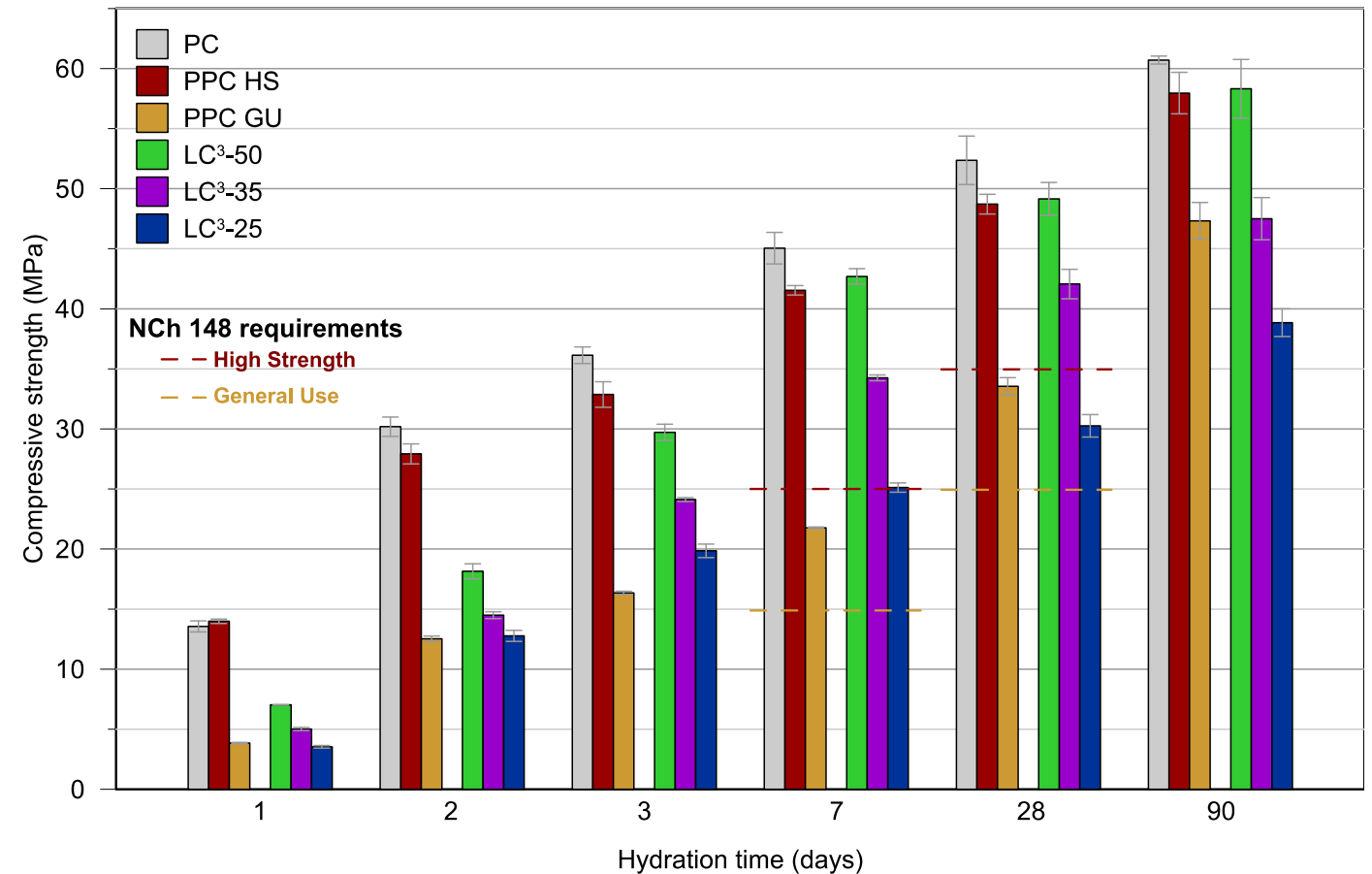
LC³ versus portland pozzolanic cements (NP) from the Chilean market

PPC HS : 80% CK

PPC GU : 65% CK

PPC HS → LC³-35

PPC GU → LC³-25



Save 40-45% clinker with LC³ compared to NP

What explains this substantial difference in performance?

Reactivity overview of LC³

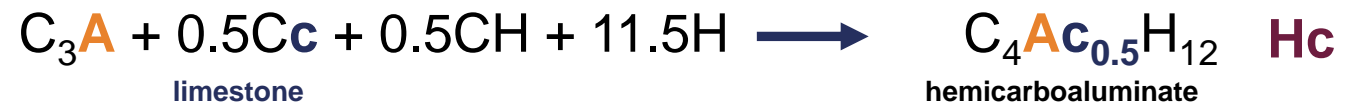
A: Al₂O₃ H: H₂O
S: SiO₂ c: CO₂
C: CaO



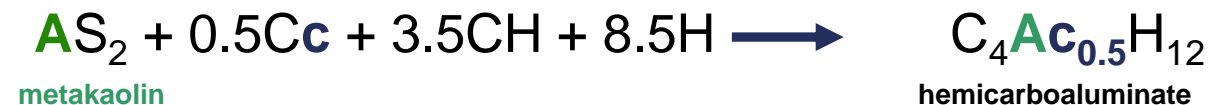
Calcined clay (metakaolin)



Limestone reaction with clinker aluminates



Limestone reaction with aluminates from calcined clay



Relevant for Type IL cements

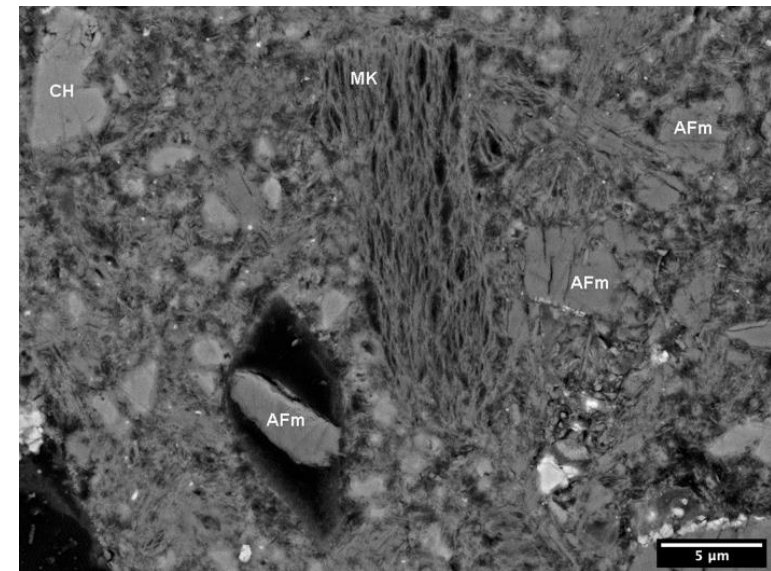
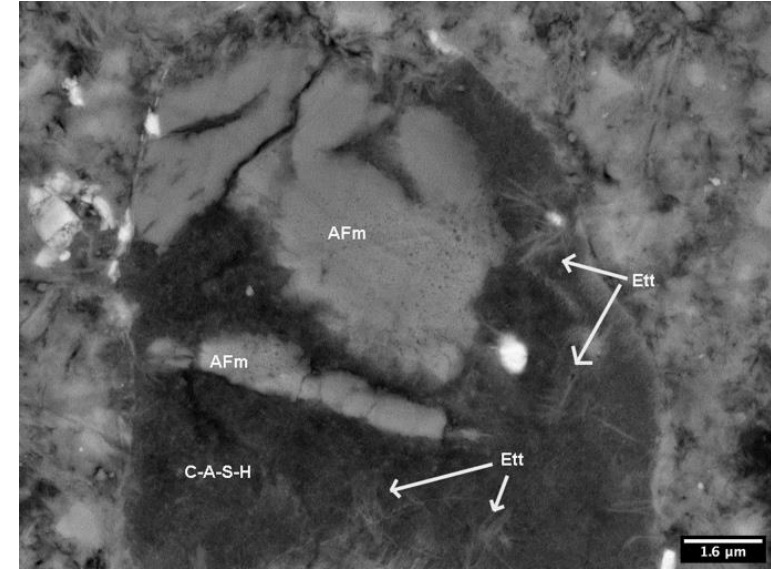
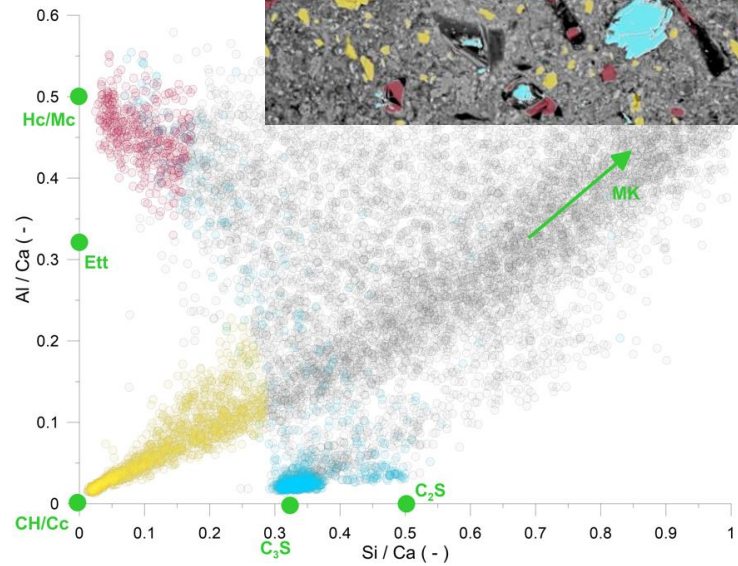
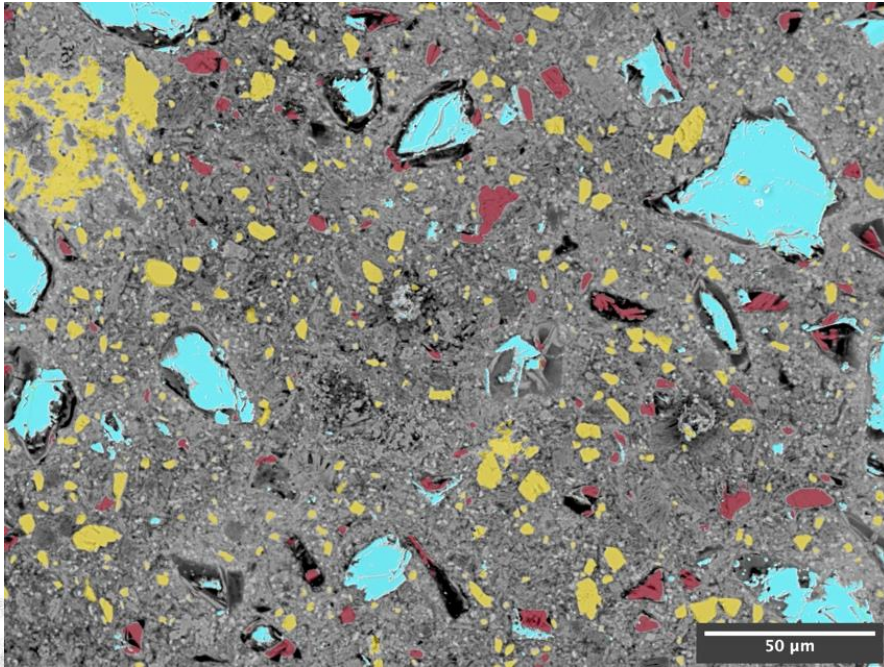
Limited by **A** availability (5-10% replacement)

Additional **A** source to sustain **Hc/Mc**

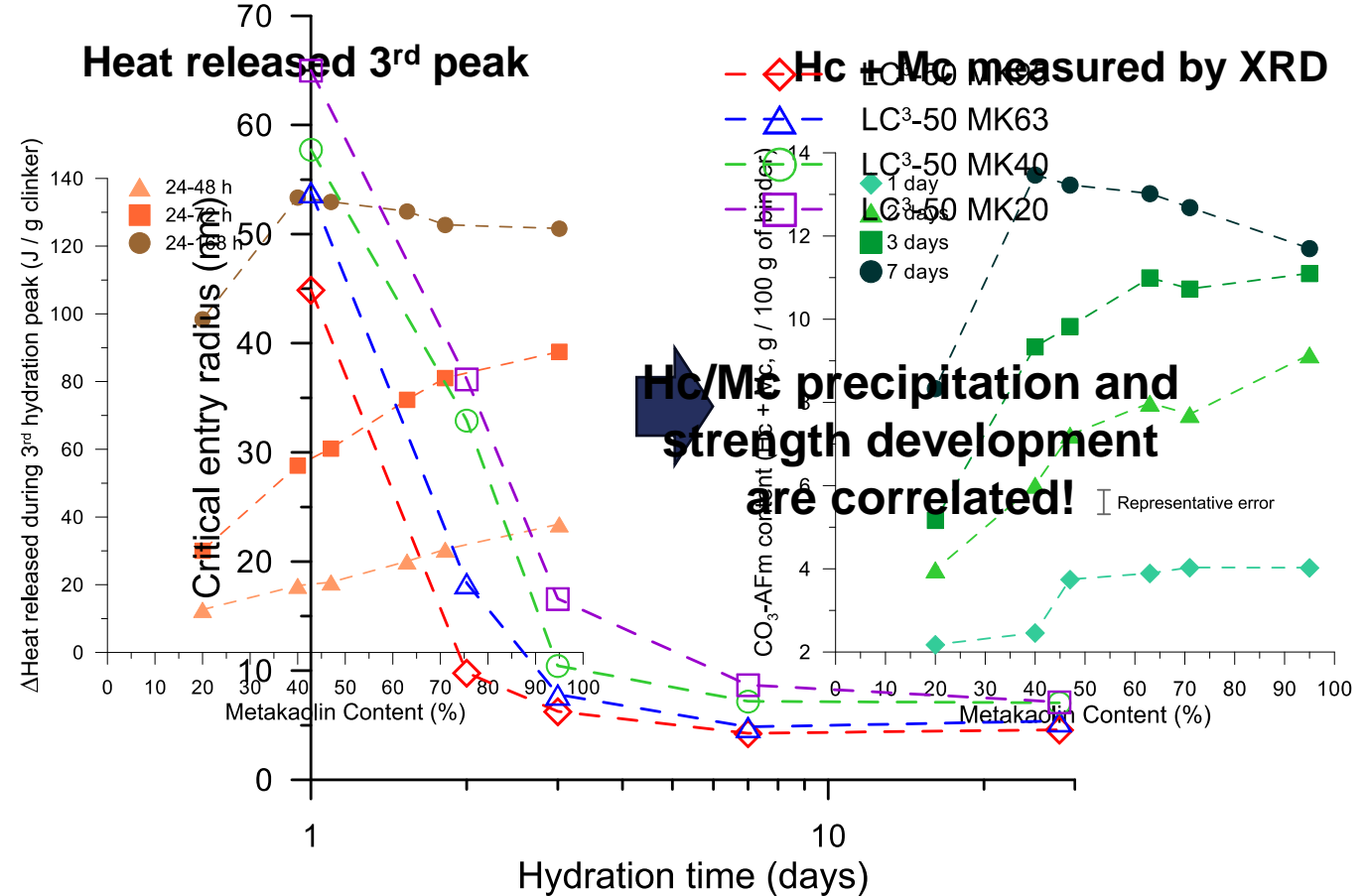
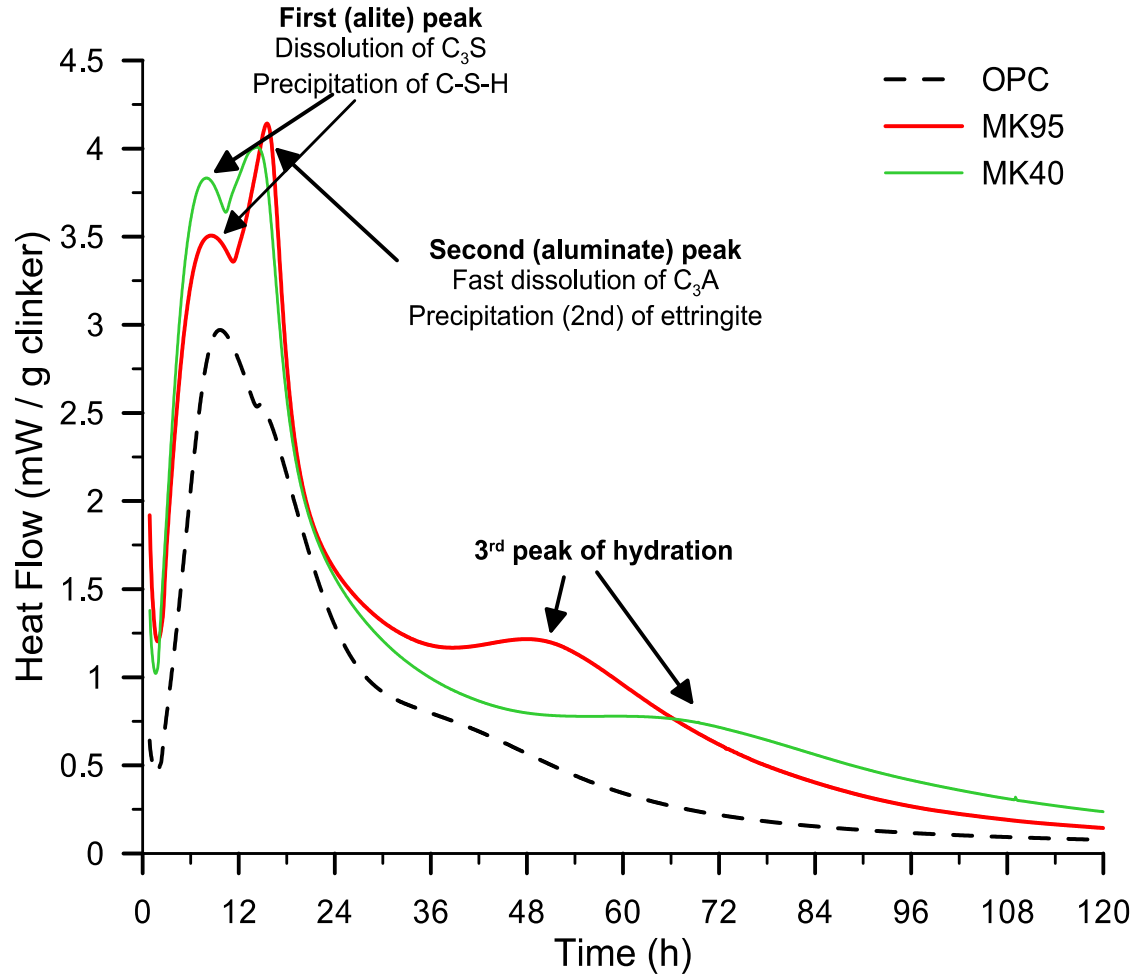
Synergic reaction of limestone and c. clay

Microstructural effects of carboaluminate precipitation

Hc, Mc
CH, Cc
Anhydrous

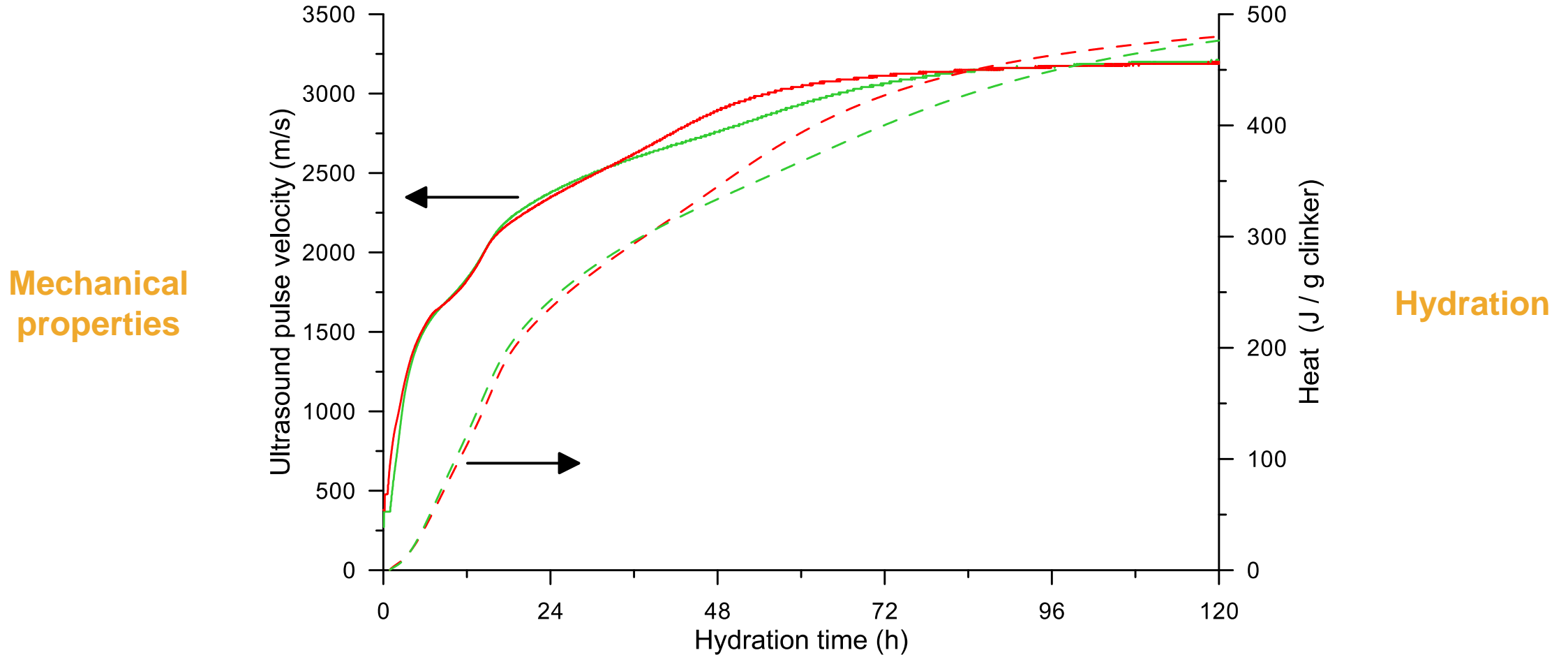


Third peak of hydration and Hc/Mc precipitation



The third peak of hydration in LC³ corresponds to the enhancement of Hc/Mc precipitation (48-72h)

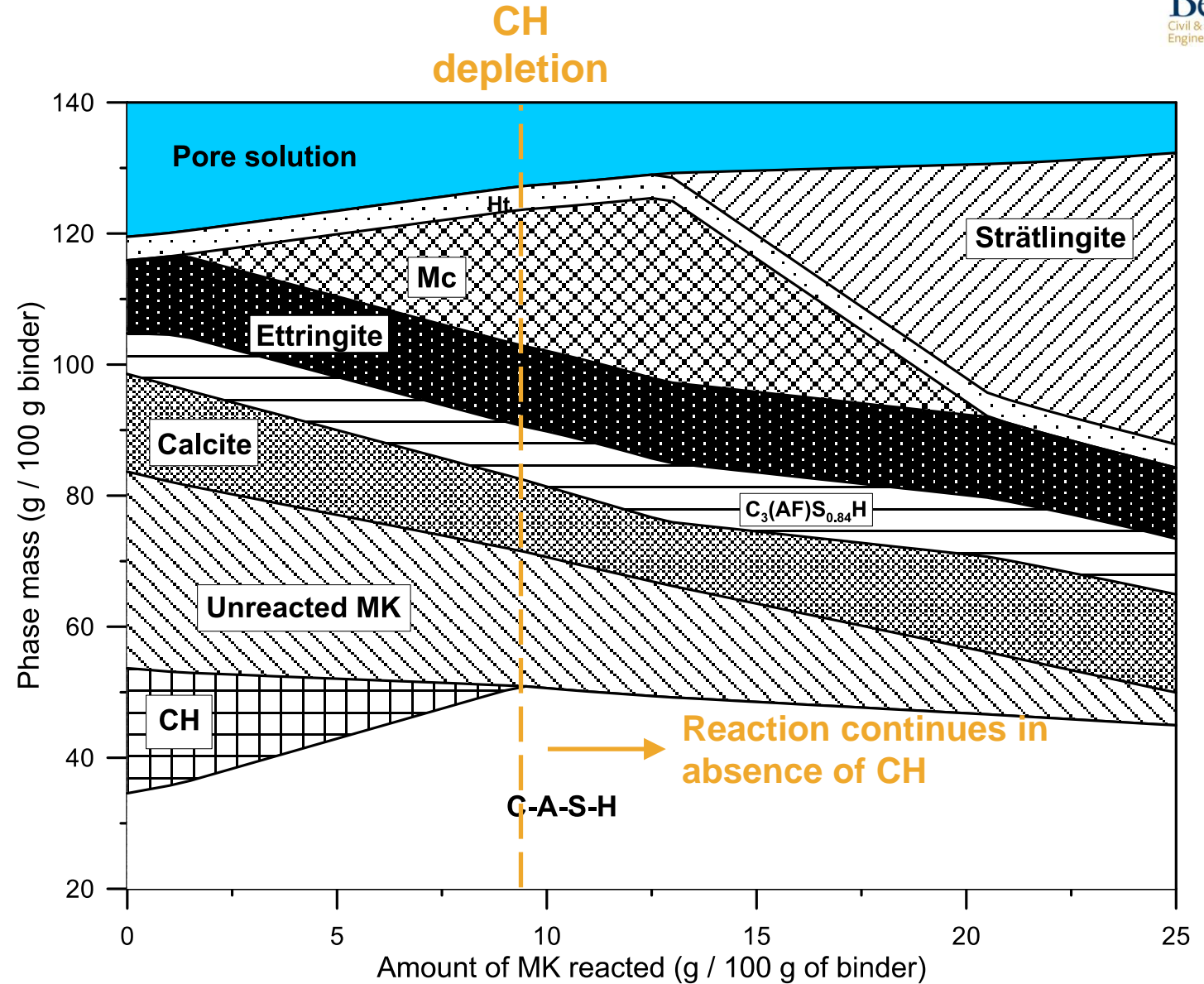
Evidence of Hc/Mc precipitation on mechanical properties



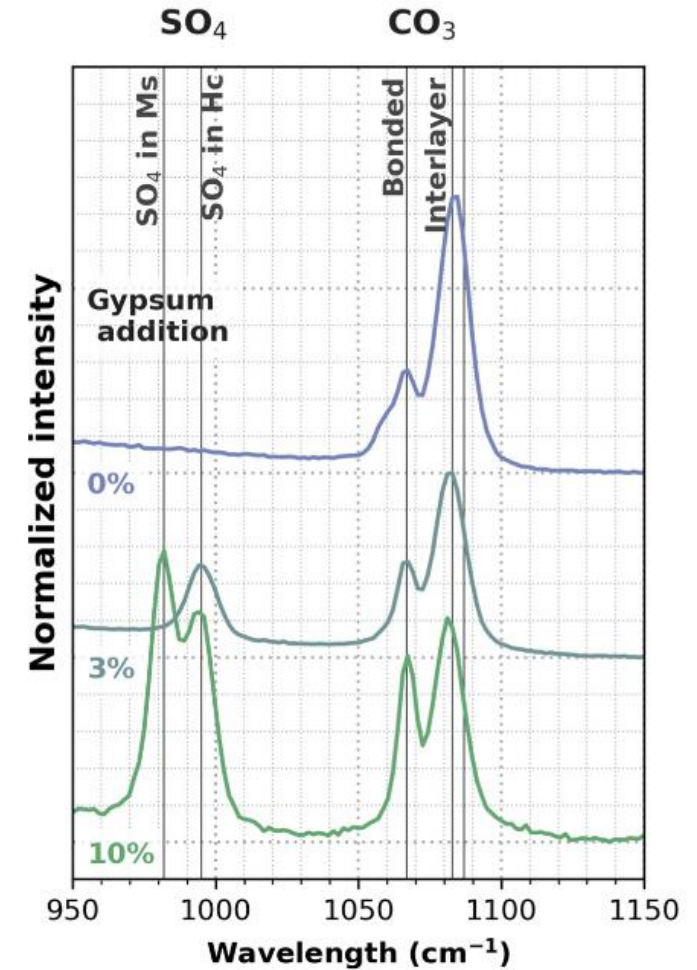
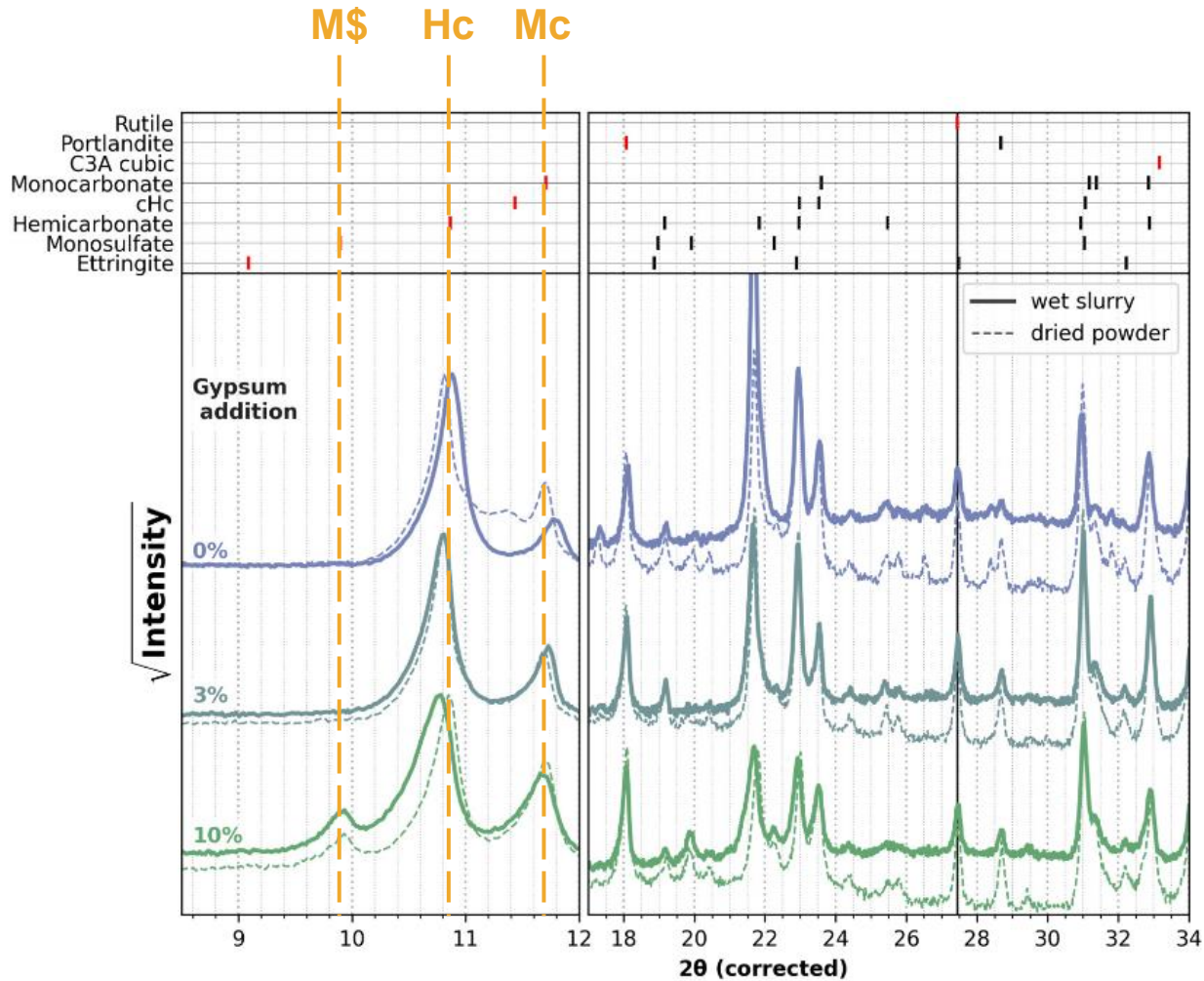
Hc/Mc precipitation can be directly associated with the increase in compressive strength between 48-72h

Equilibrium phase assemblage of LC³ as function of MK DoR

Independent of the extent of MK reaction, only Mc is predicted to form by TM

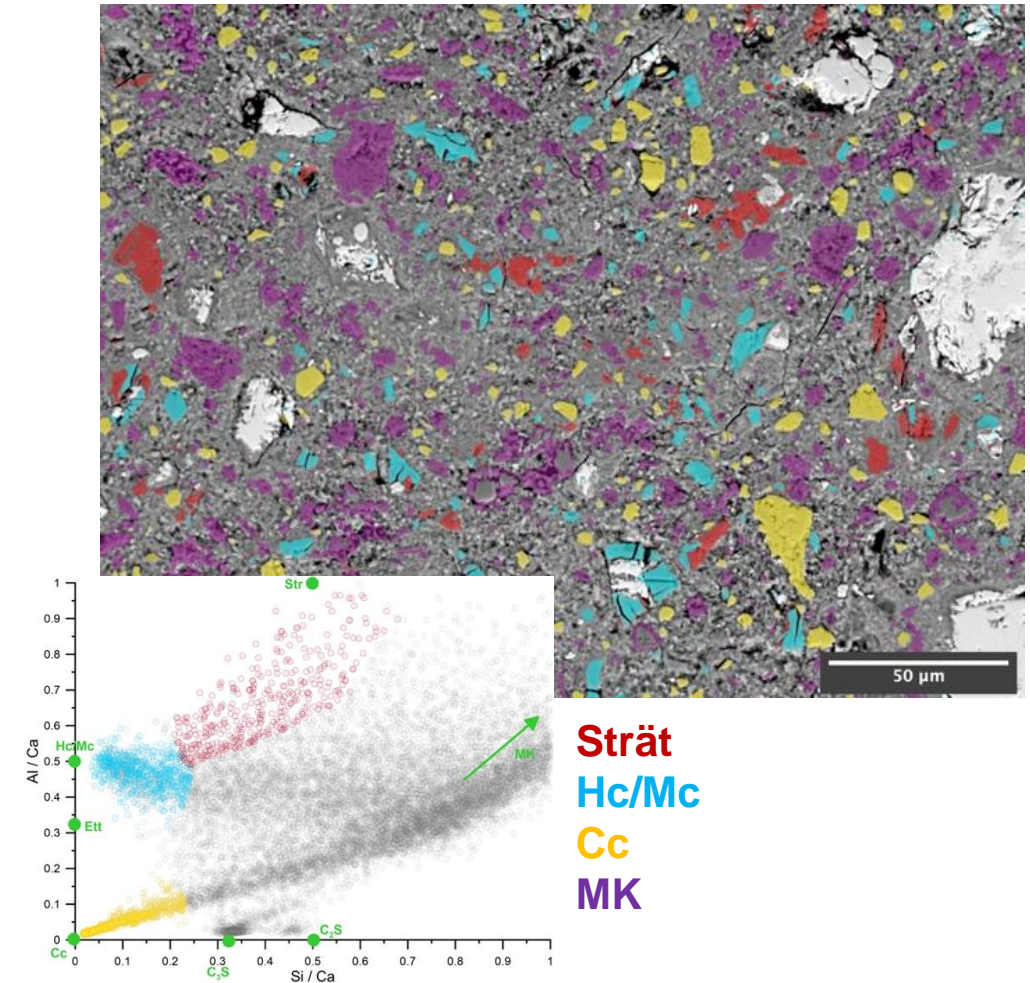
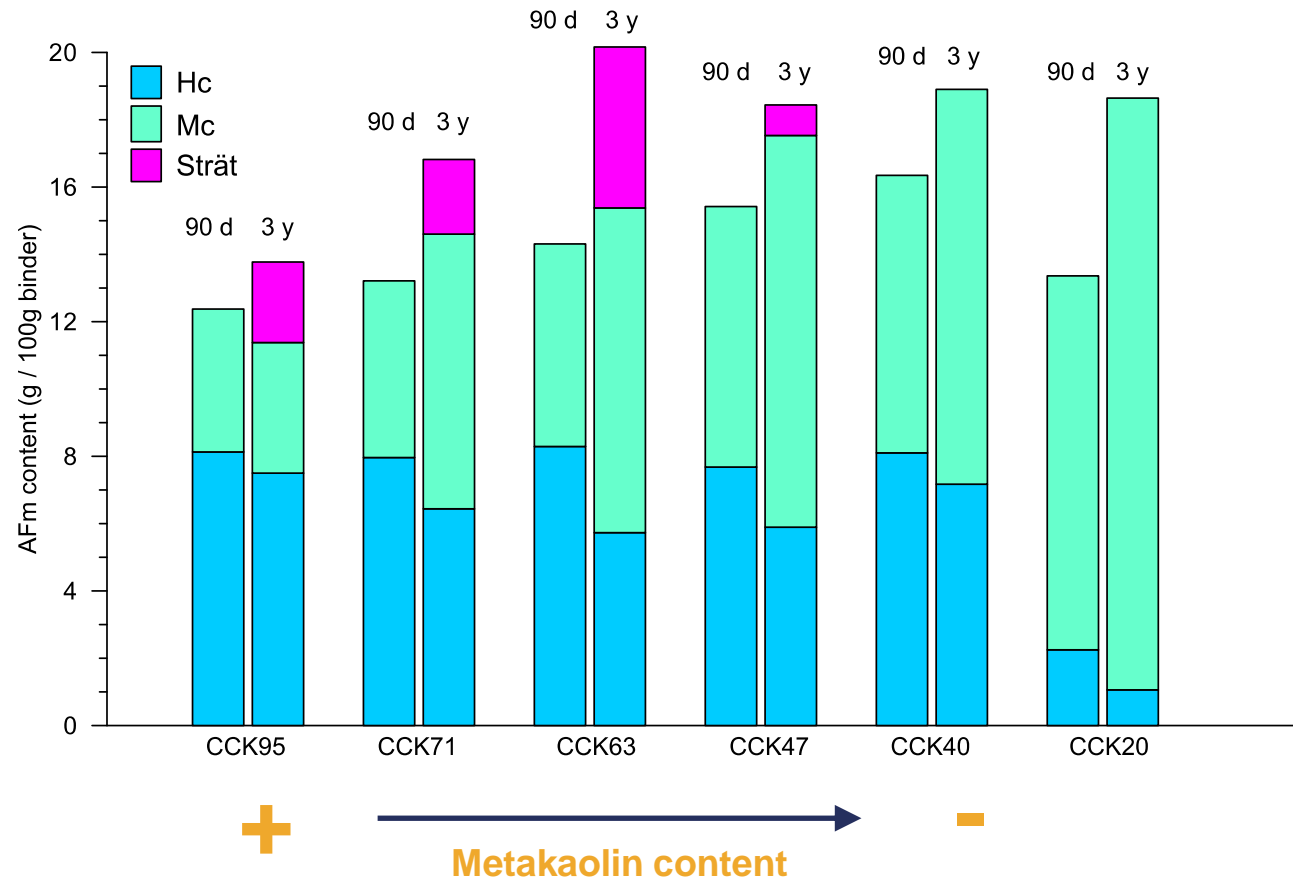


Long-term stability of hemicarboaluminate (Hc)



Incorporation of SO₄²⁻ into the Hc lattice might explain the long-term stability of this phase

Long-term (3 yr) phase assemblage in LC³ cements

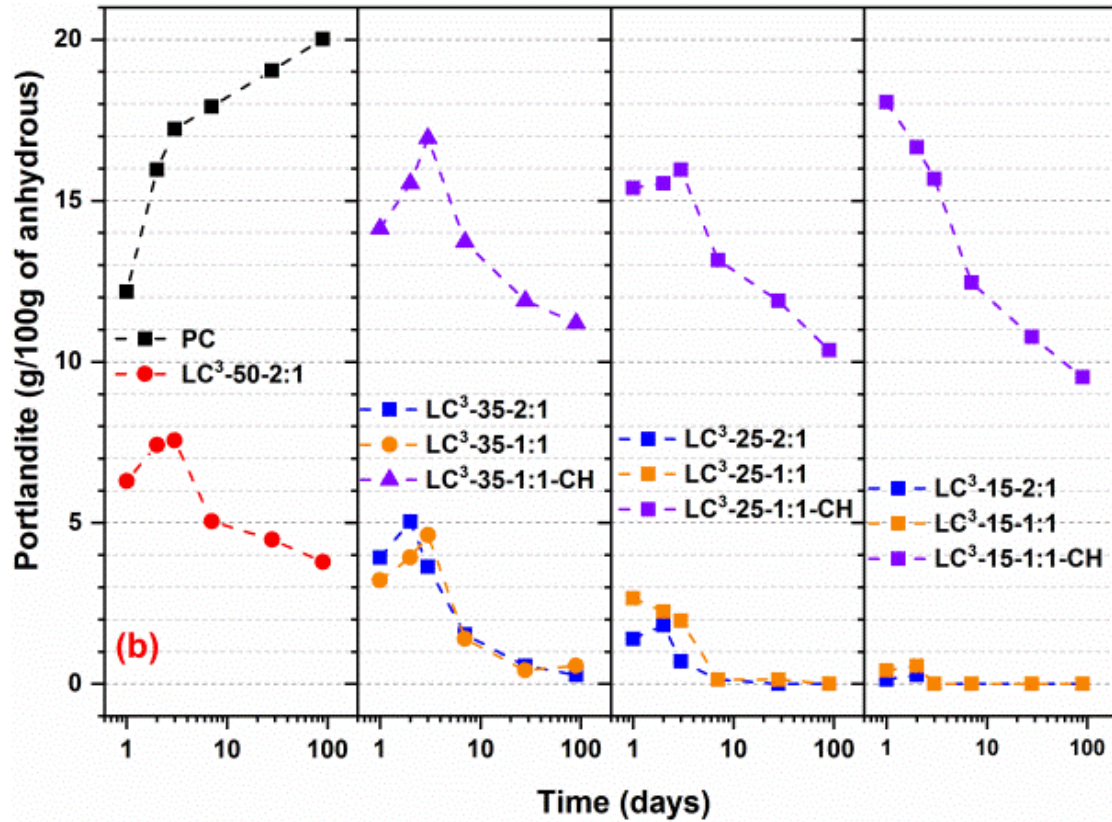


Strätlingite observed in systems with high MK content. Partial conversion of Hc to Mc, however Hc is still observable in all systems.

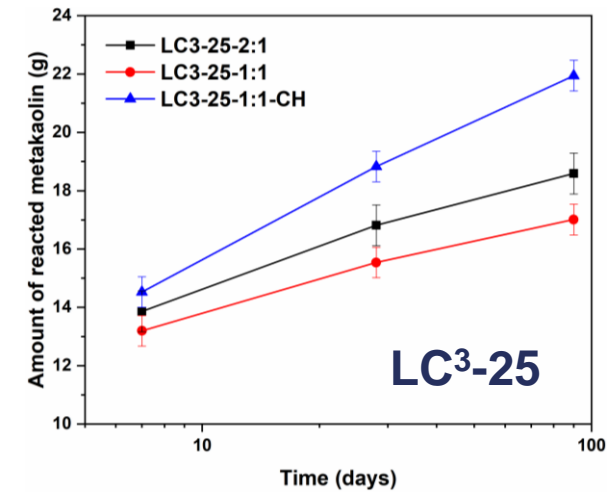
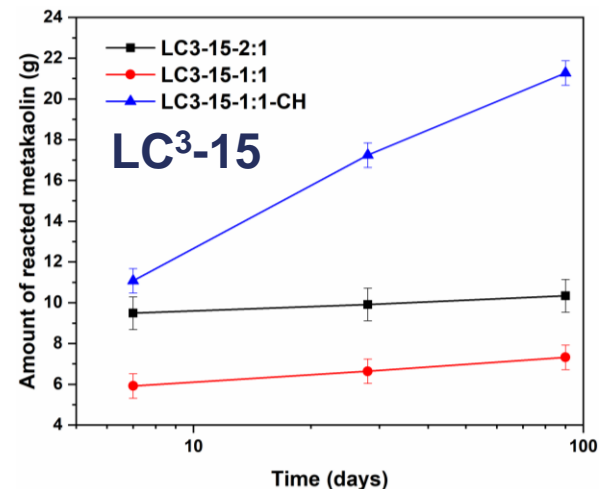
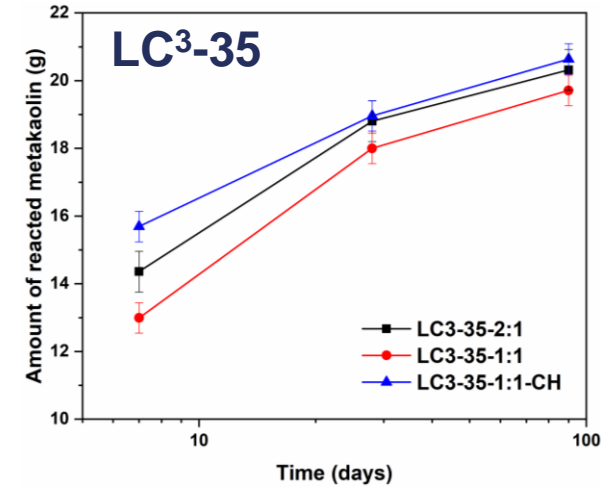
Implications for low-clinker (<50%) LC³ cements

Metakaolin reactivity in low clinker systems

Degree of reaction of MK



CK 50% : CH is not limiting factor
 CK <50% : CH is a limiting factor

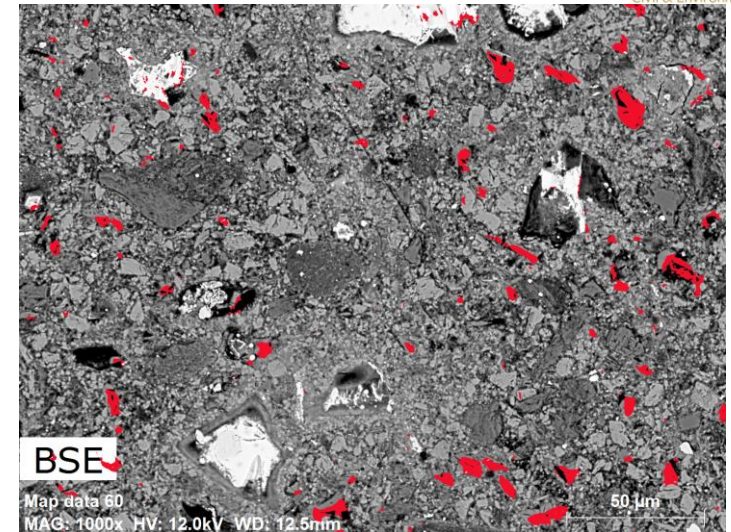
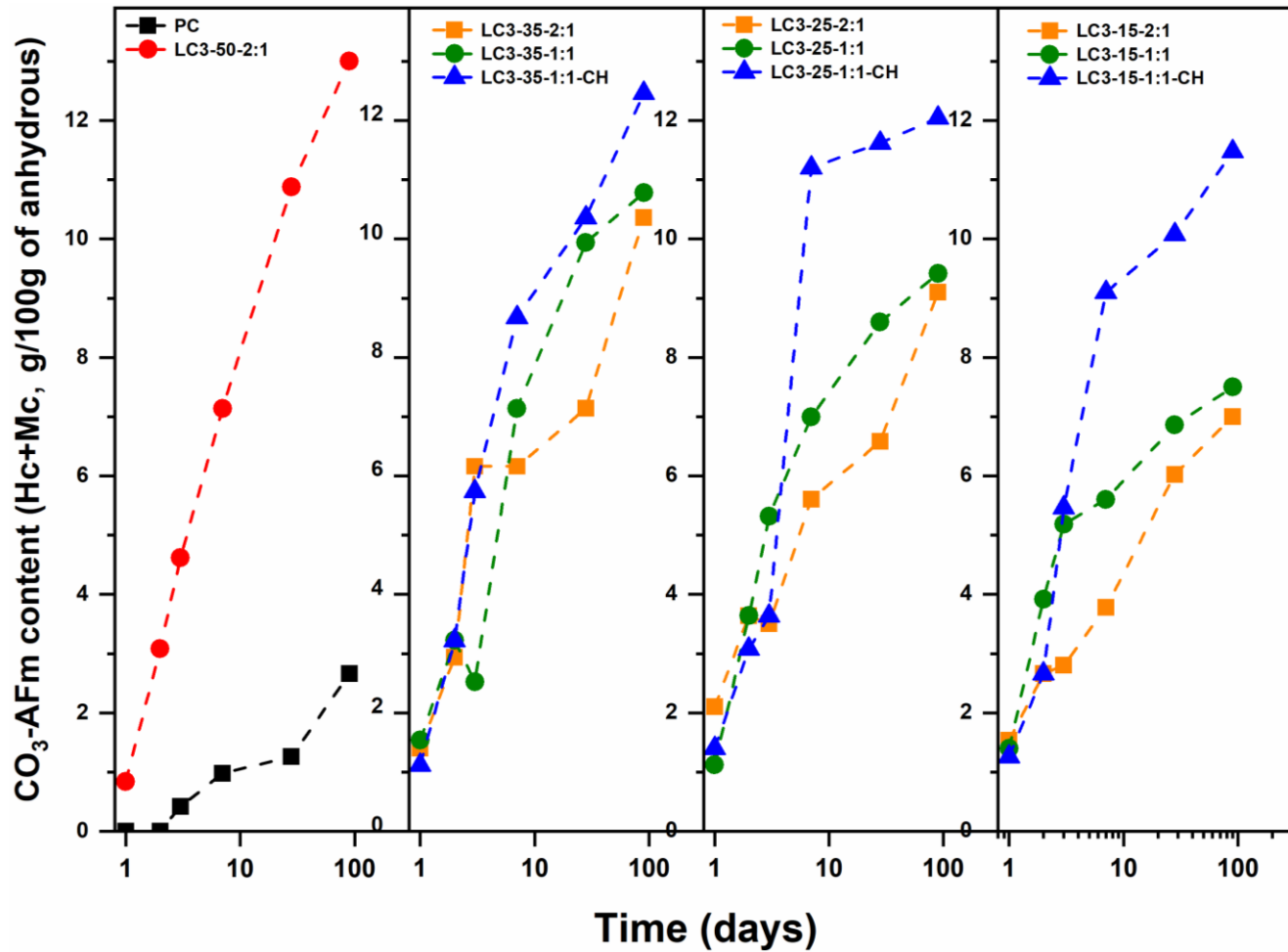


Additions of CH enable and increased degree of MK reaction

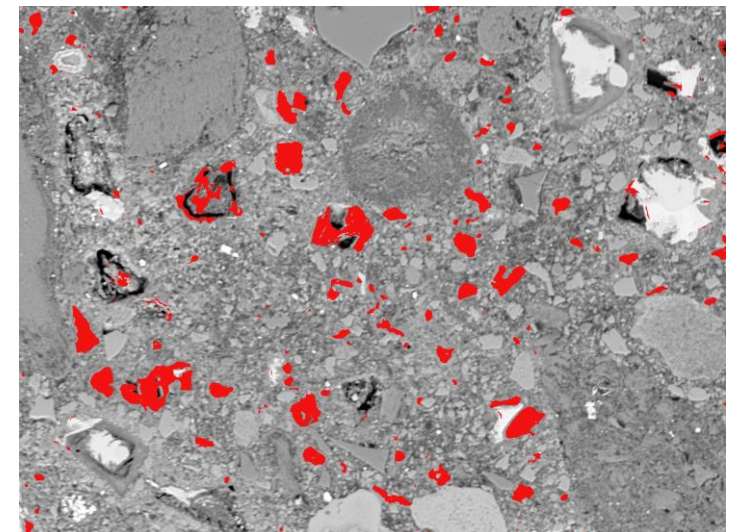
Metakaolin reactivity in low clinker systems

Precipitation of carboaluminates

Hc/Mc

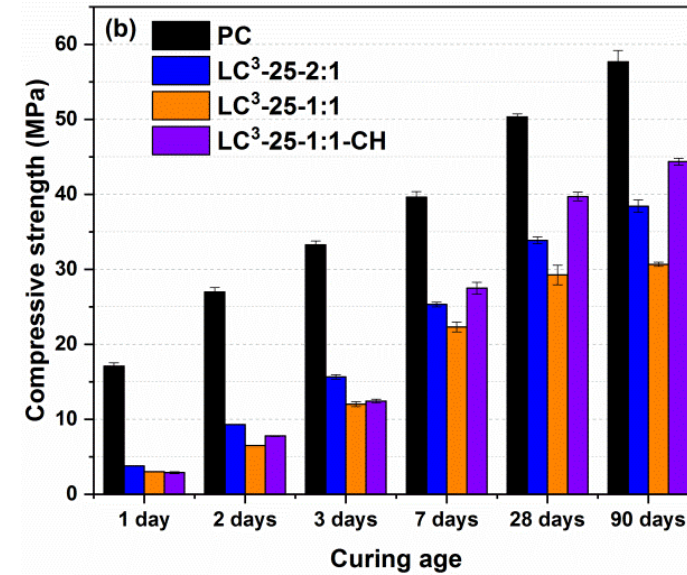
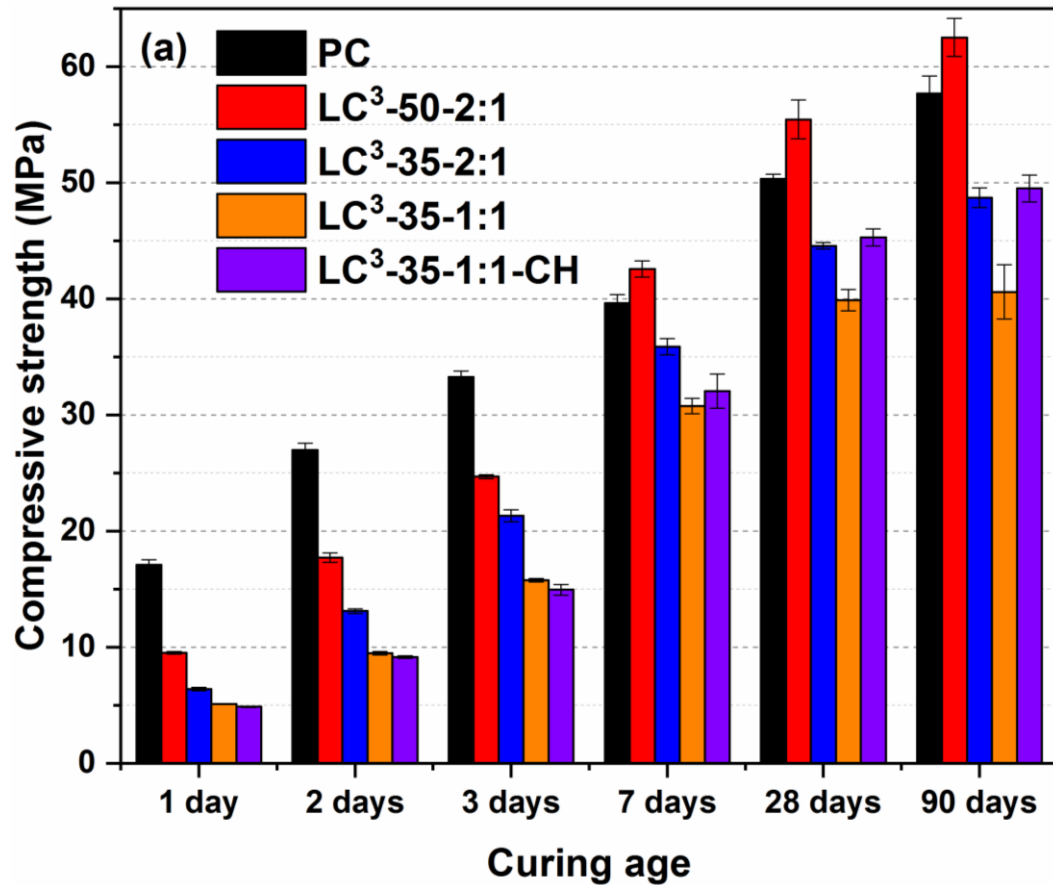


LC³-25-1:1-28days AFm area: 2.49%

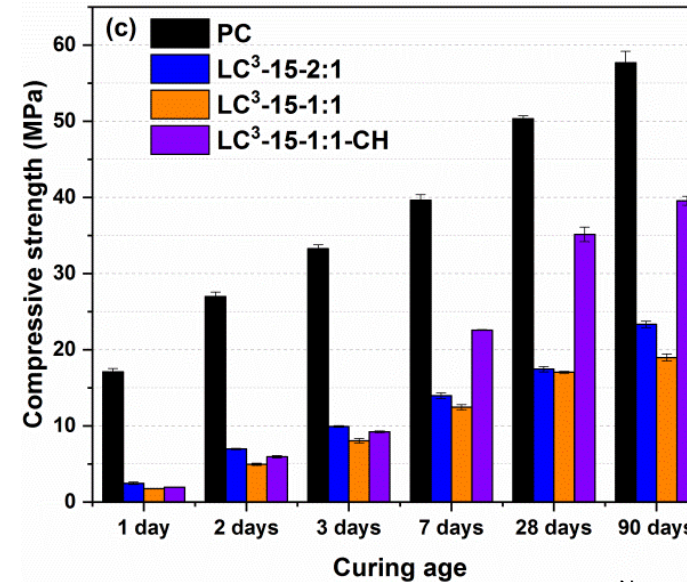


LC³-25-1:1-CH-28days AFm area: 4.37%

Strength development enhanced by CH additions



LC³ – 25



LC³ – 15

However we do not solve the 1-2 day strength issue
and CO_{2e} CH > CO_{2e} PC

Concluding remarks

- LC³ cements **decrease their porosity considerably between 48-72h**, leading to an increase in strength that ultimately matches OPC (at 50% clinker factor).
- The **decrease in porosity is associated with the precipitation of carboaluminates** (hemi and mono), which effectively fill large capillary pores that remain after alite dissolution.
- From a kinetic standpoint, the **precipitation of carboaluminates can be associated with the 3rd peak of hydration**. Carboaluminates only precipitate after gypsum depletion.
- **Hemicarbonate incorporates sulfate in its lattice**, likely explaining its long terms stability. Better thermodynamic data of CO₃-AFm solid solutions is urgently needed.
- In low-clinker LC³, **the contribution of carboaluminate precipitation to strength development is even higher** than in materials with 50+% clinker.

Thank you for your attention

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