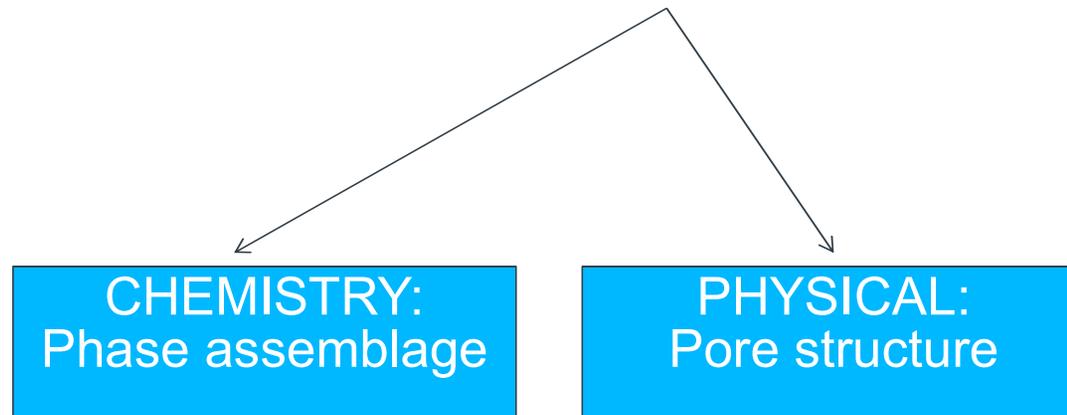


# Durability

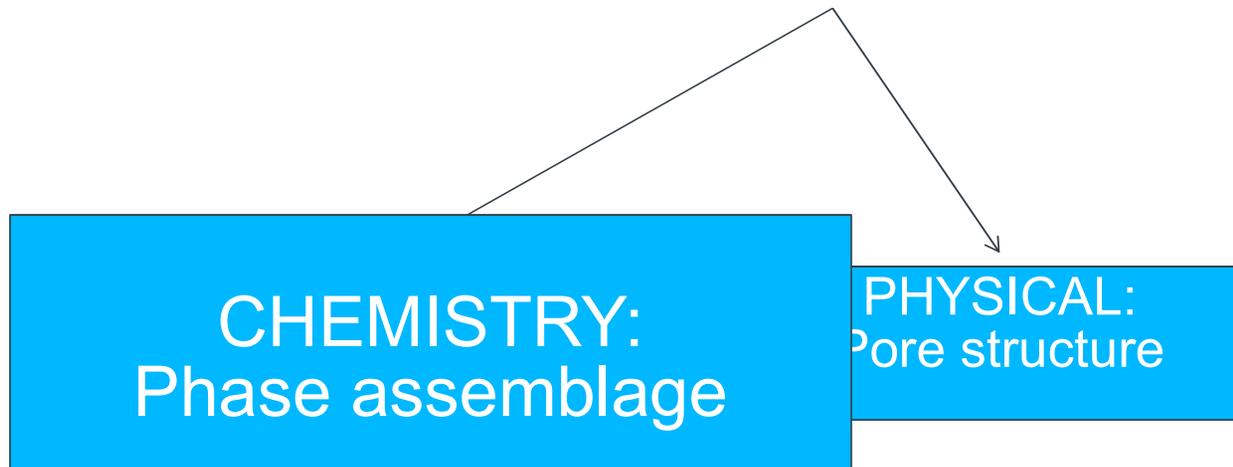
## Generic approach to durability

Durability determined by microstructure:

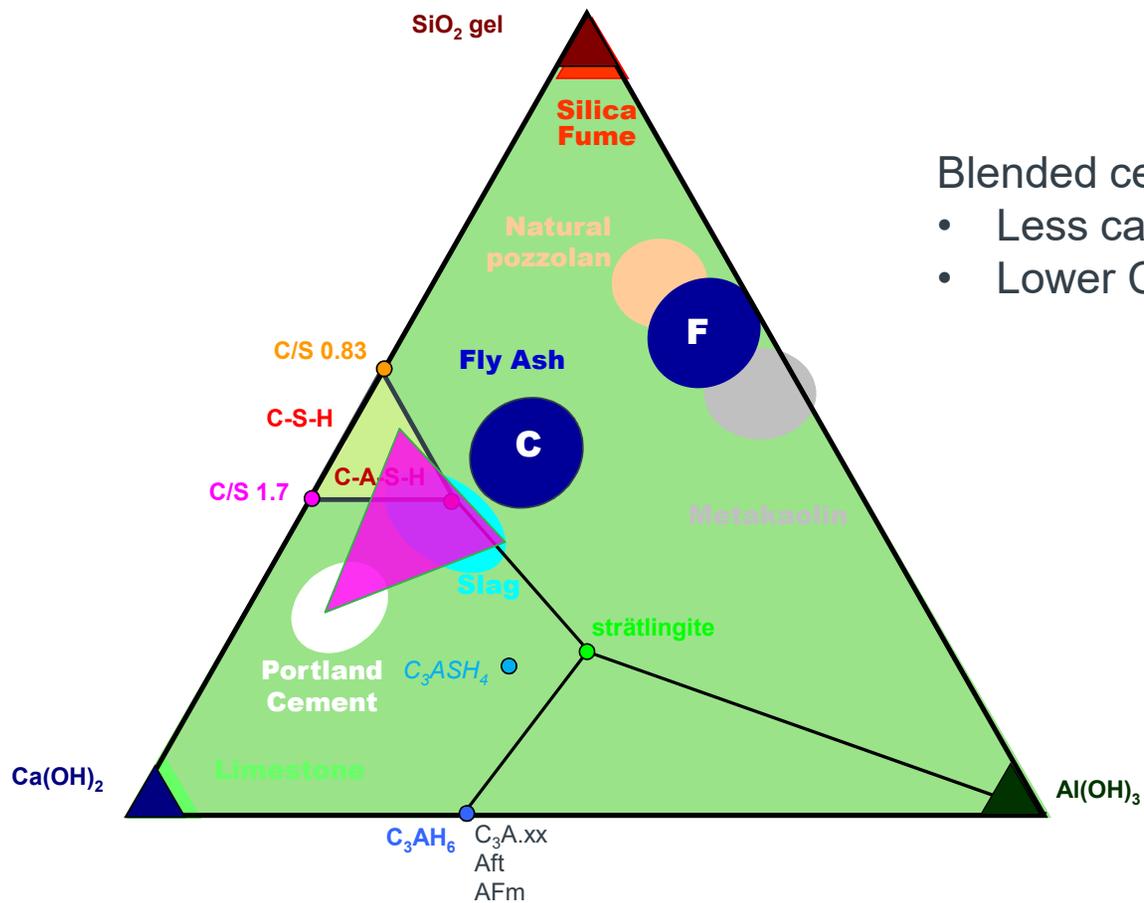


## Generic approach to durability

Durability determined by microstructure:



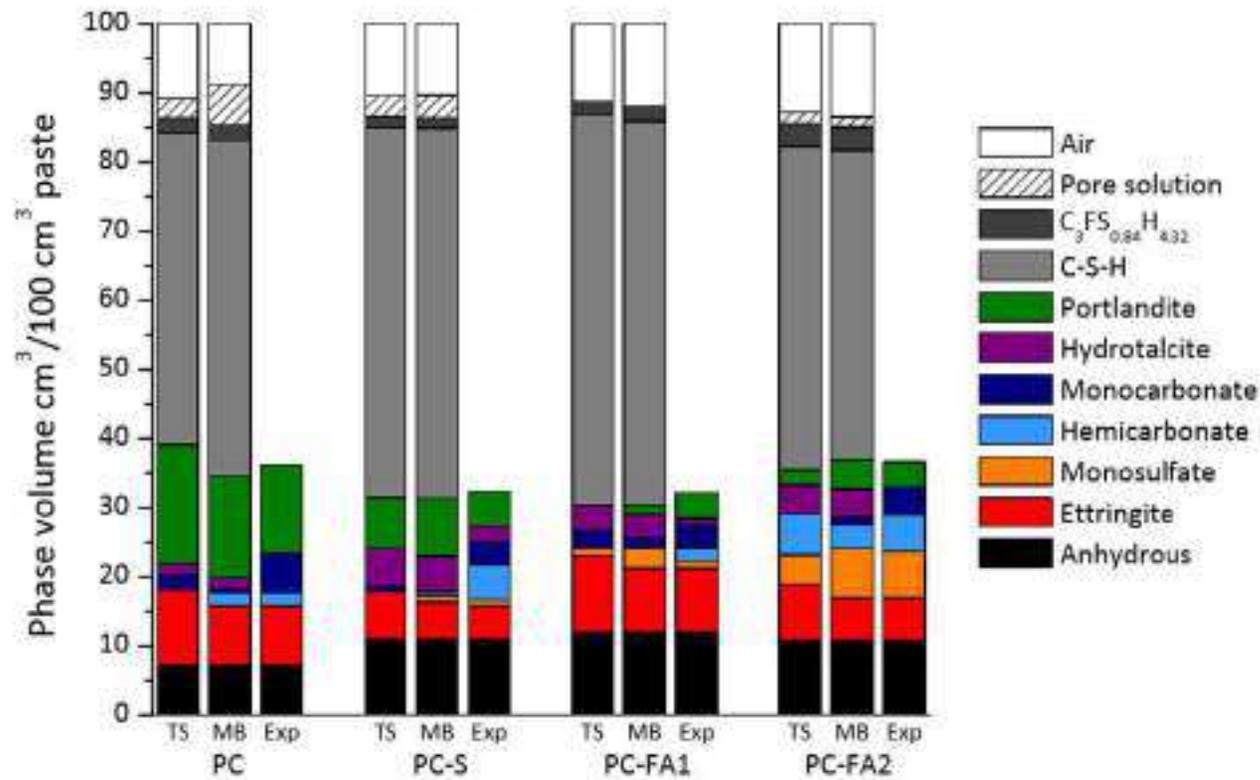
# Main components CaO-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>



Blended cements:

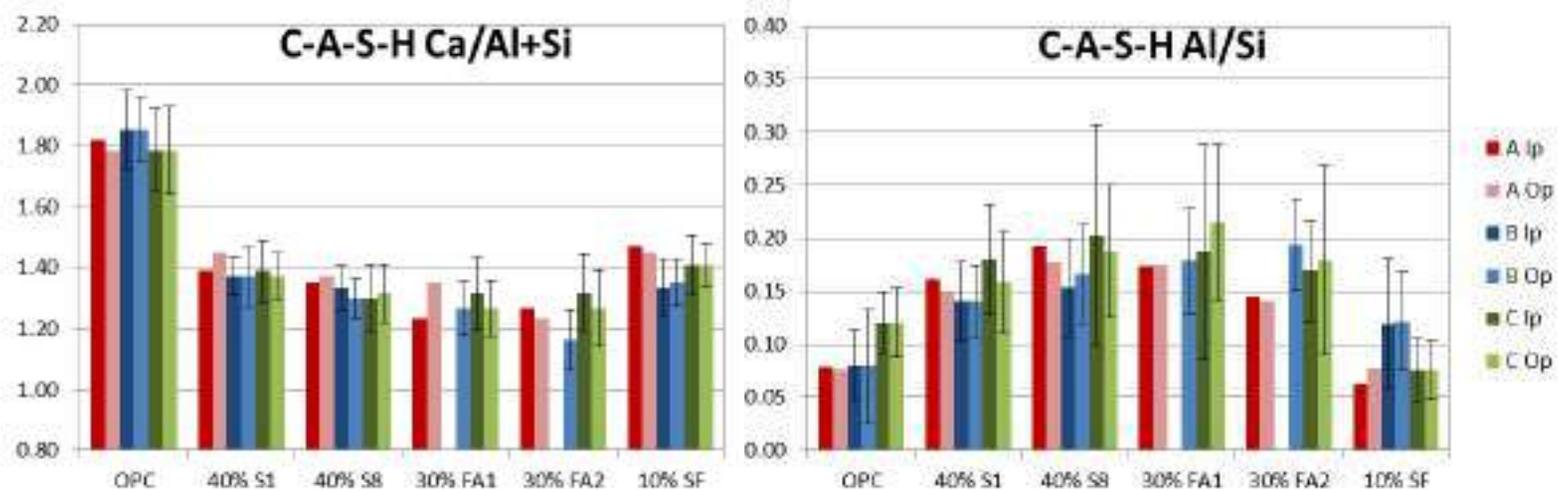
- Less calcium hydroxide
- Lower Ca/Si C-S-H

thermodynamics and experiment



Durdzinski et al CCR 2017

## Composition of C-A-S-H after 4-5 years

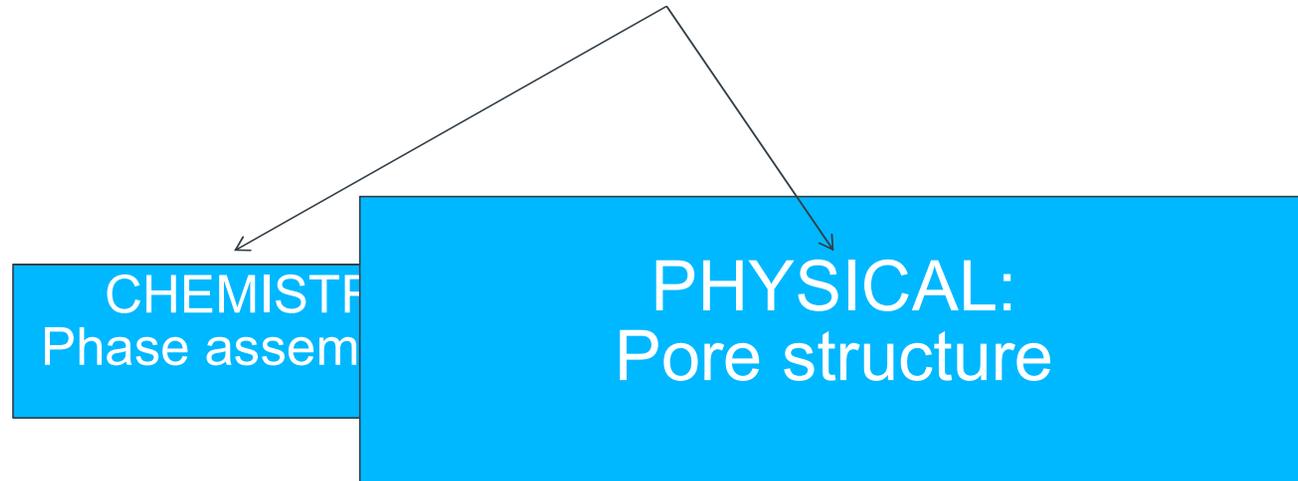


Very similar C/S ratios – stabilised by presence of Portlandite  
Al usually higher, approaching Al/Si = 0.2 (except SF no Al)

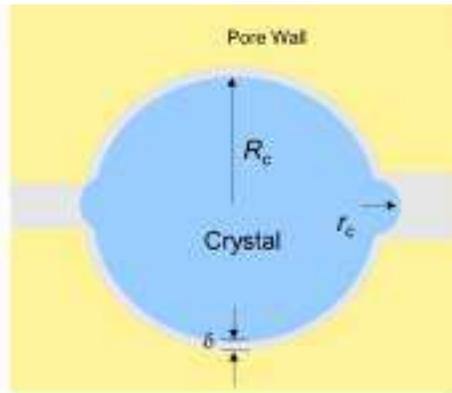
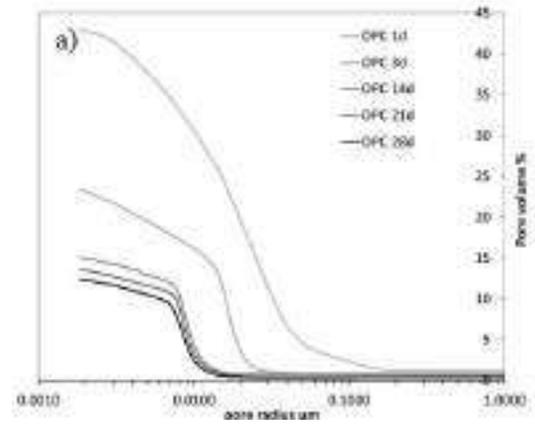
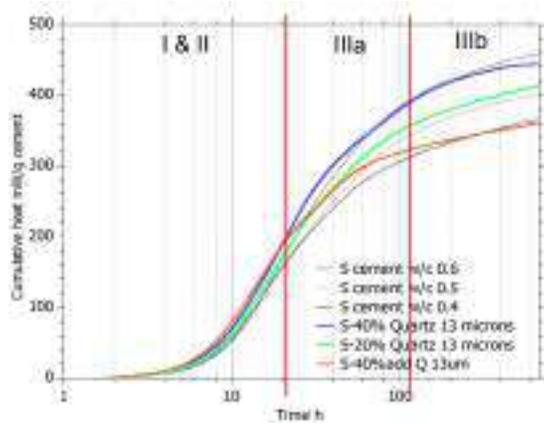
Degradation phenomena	Impact of hydrate phases
<b>Chloride ingress</b>	Aluminate containing hydrates react to bind chloride ions in Friedel's salt, Chloride also absorbed on C-S-H
<b>Carbonation</b>	Calcium oxide in all hydrates will eventually form calcite leaving hydrated silica and alumina gels
<b>Sulfate ions</b>	AFm phase react with sulfate ions to form ettringite, if these phases are confined within the C-S-H and the solution is supersaturated expansion may occur
<b>Alkali silica reaction</b>	Absorption of alkali ions on C-S-H determine the pH of the pore solution. Reactive alumina from SCMs may also directly inhibit dissolution of reactive amorphous or poorly crystalline silica

## Generic approach to durability

Durability determined by microstructure:



# Limiting pore size

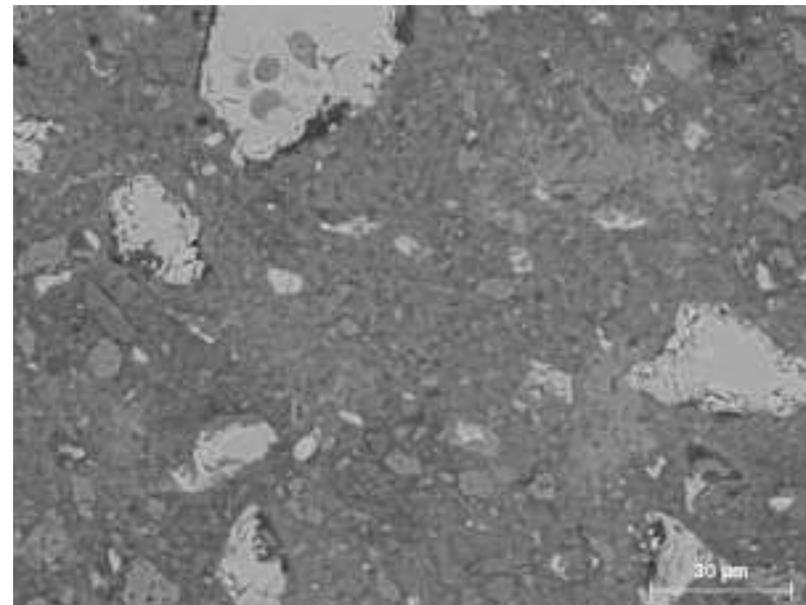
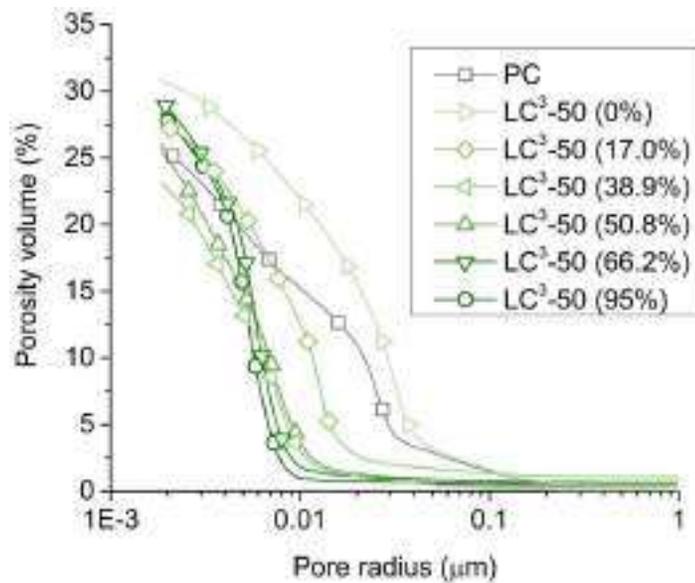


Limiting pore size for crystal growth about 10 nm

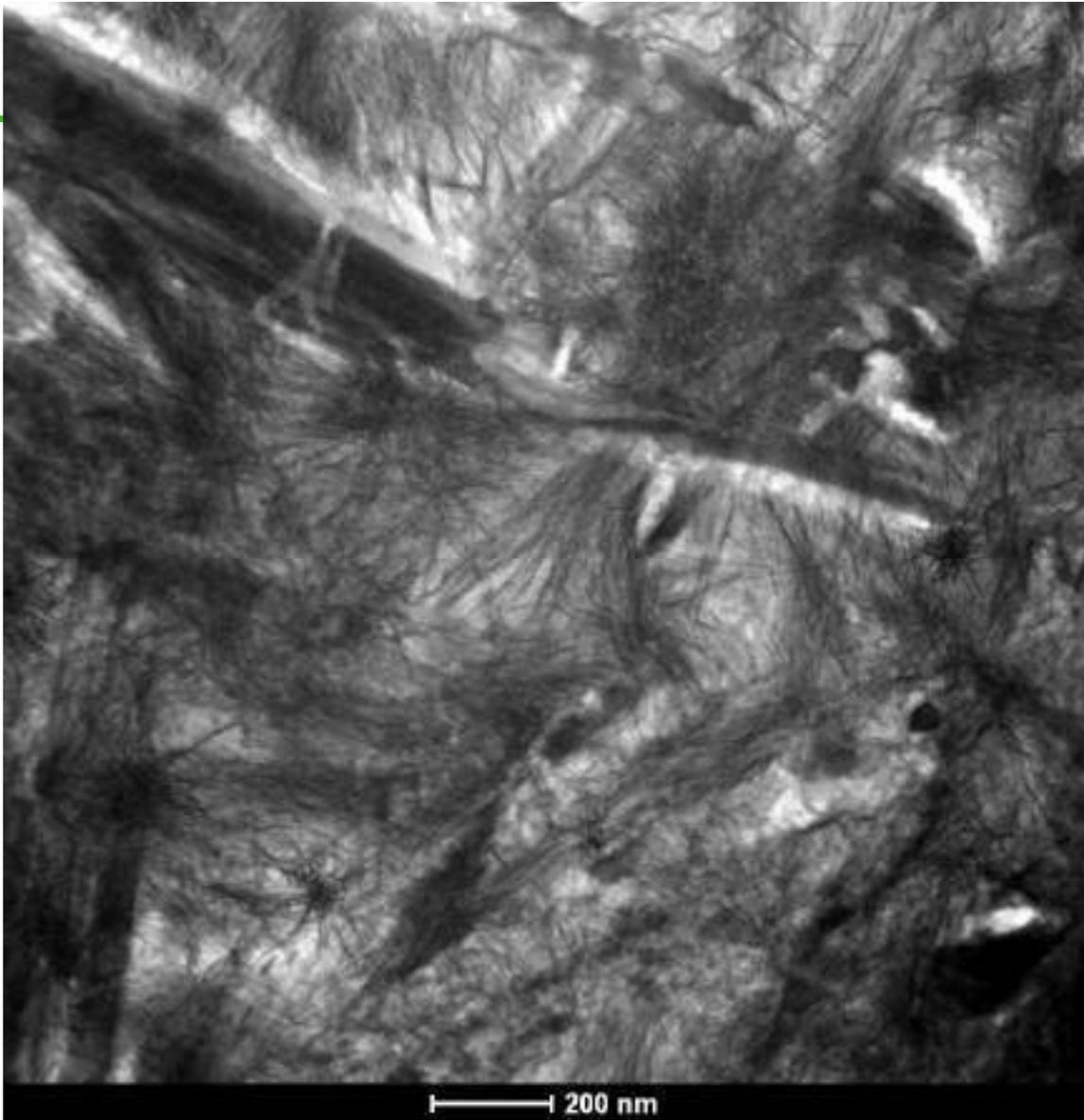
Whether this is reached depends on:

- w/c
- Curing
- Reacting phases

Most important aspect is  
the very strong refinement of porosity

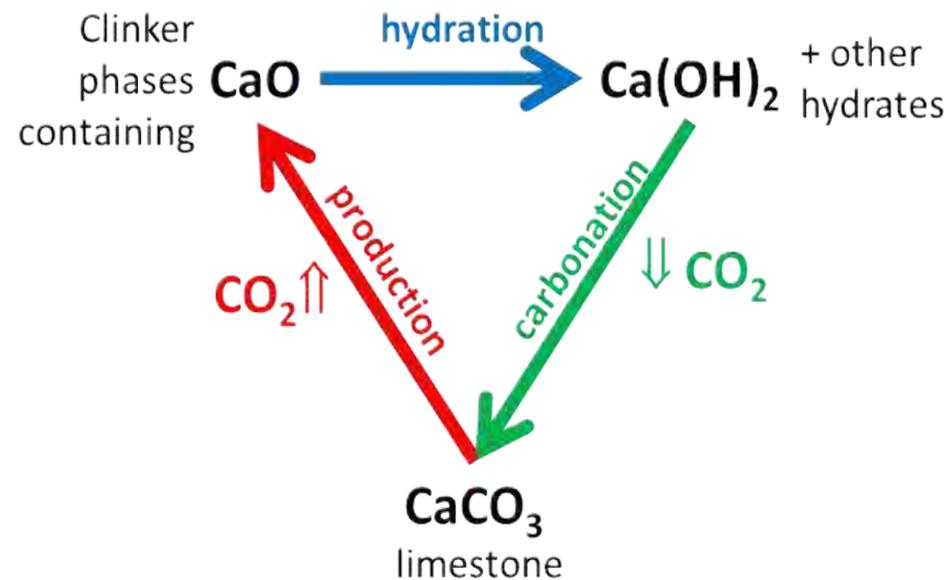


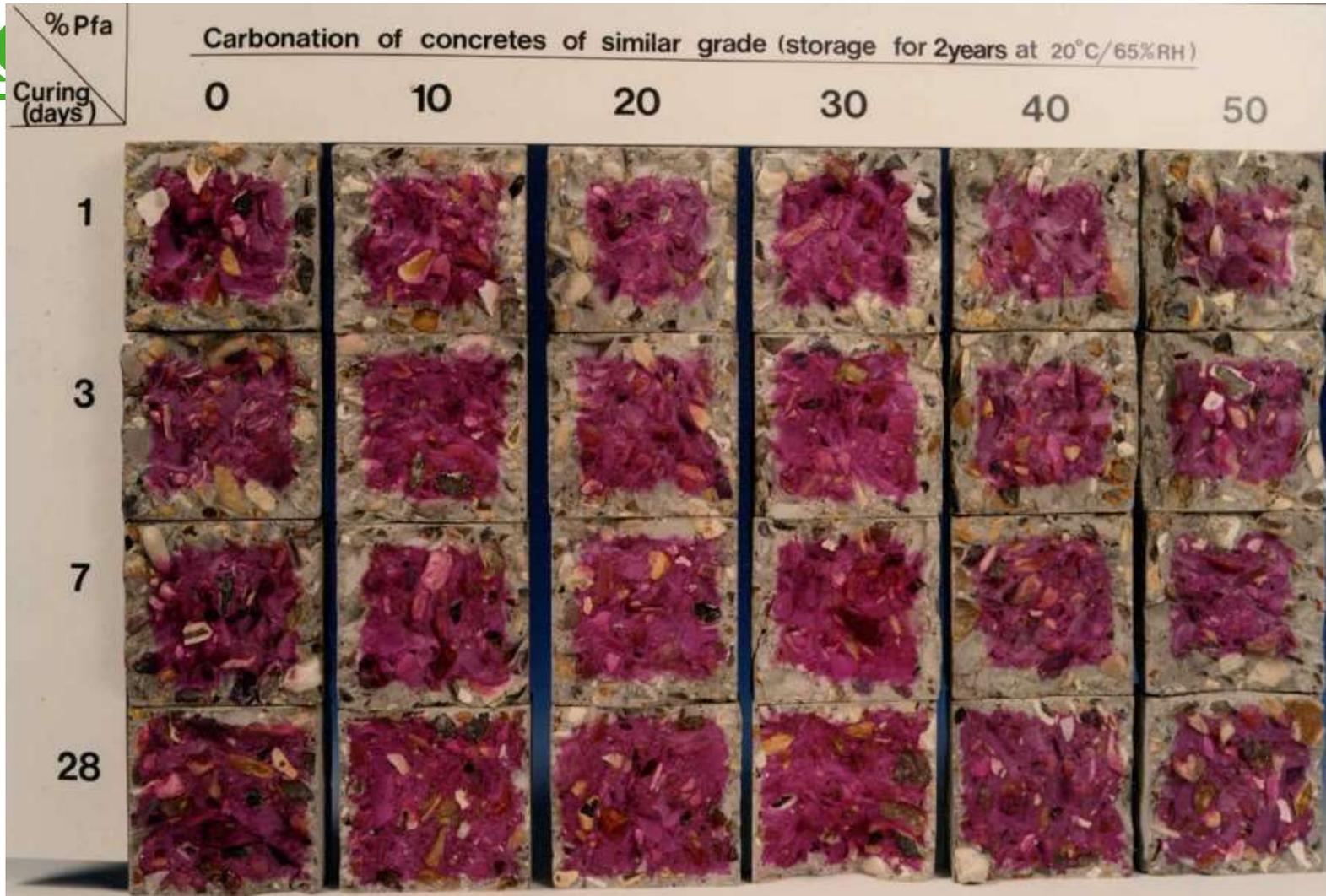
**28 days**



# Carbonation

Steel protection comes from high pH: linked to calcium content and therefore CO<sub>2</sub>

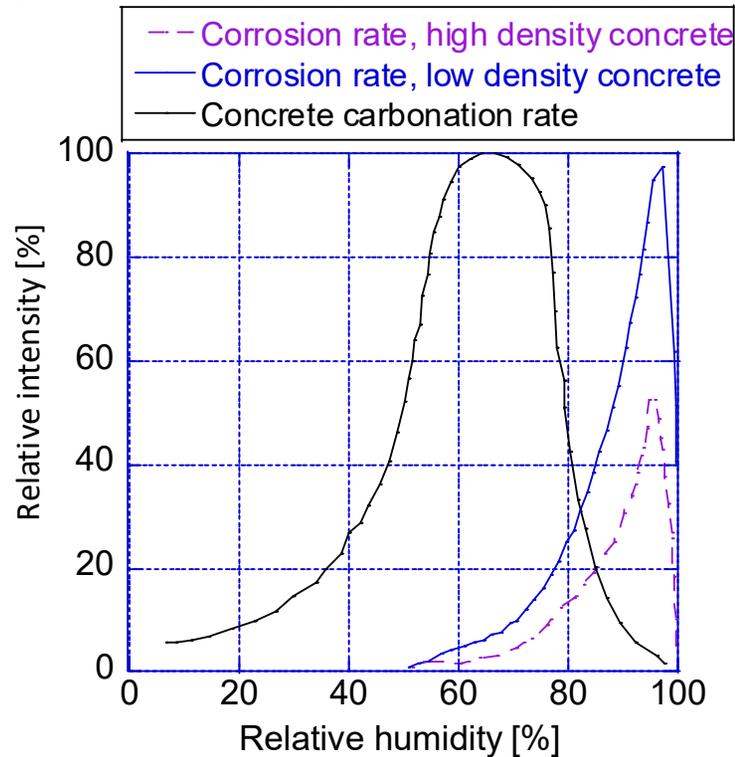




**Reduction of buffering can be offset with good curing**

From BRE via MDA Thomas, UNB

## Practical risk of carbonation corrosion ?



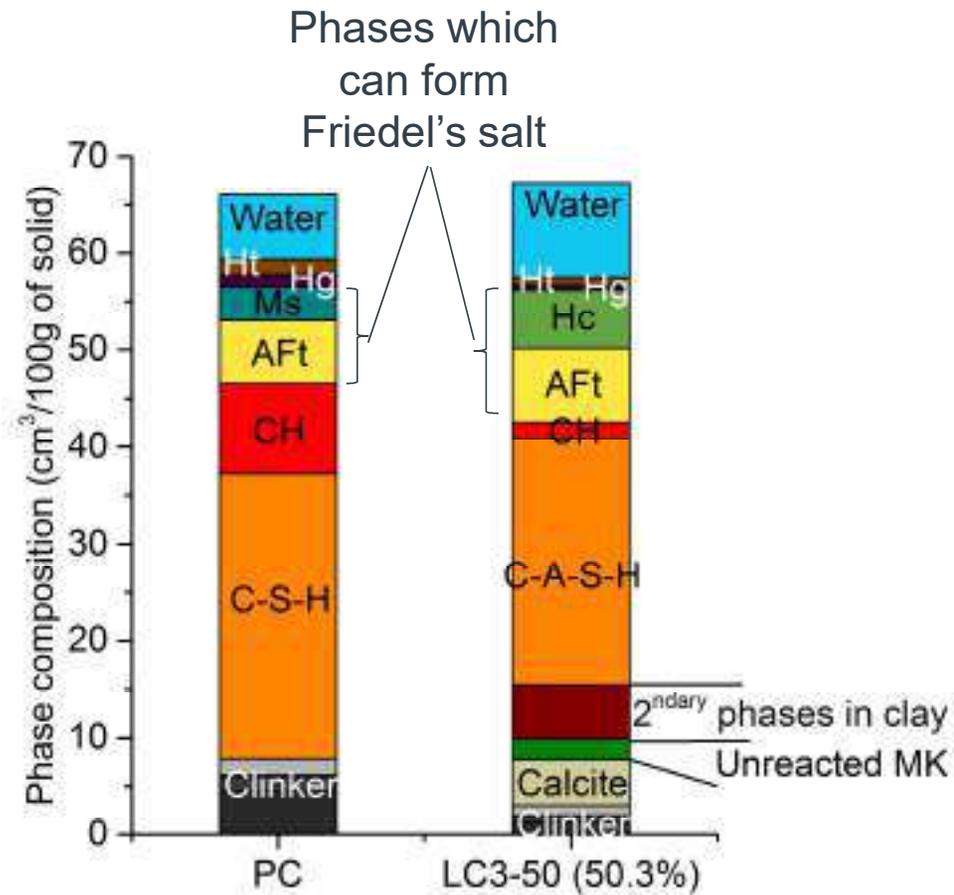
- » Carbonation takes place in environments which are too dry for active corrosion
- » Conversely conditions with enough humidity for active corrosion will only carbonate very slowly
- » Can be dealt with by correct design and cover depths

# Chloride ingress

Example of LC3 binders

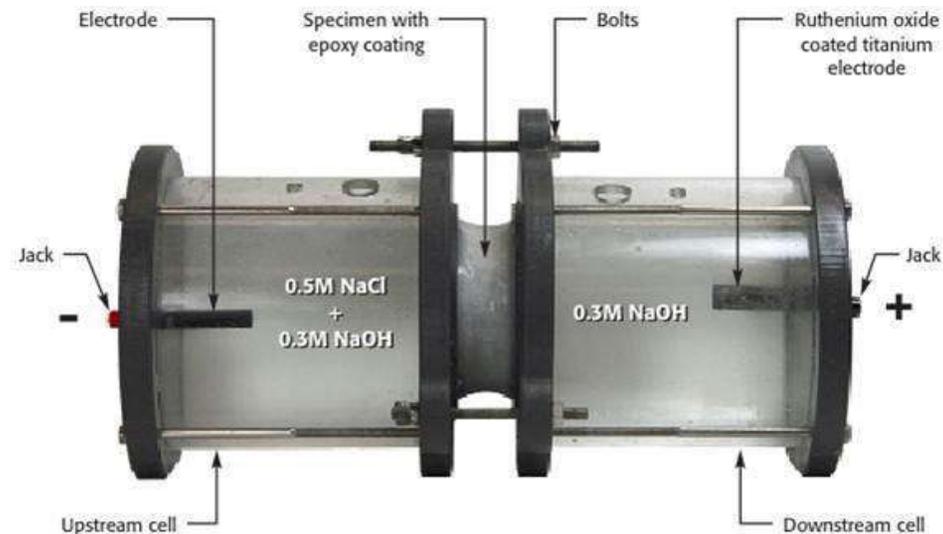


# Phase assemblage



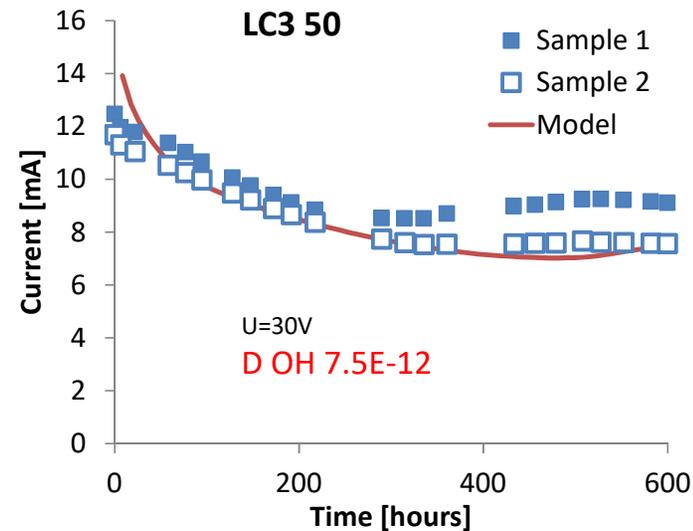
## Chloride migration test

- ASTM C1202-97: too high voltage, self heating ⇒ Modified version of the test, from SIMCO
  - Lower voltage, run for at least 10 days  
Current and Voltage monitored daily
  - Use in combination with model to estimate diffusion coefficient of ions in cementitious materials

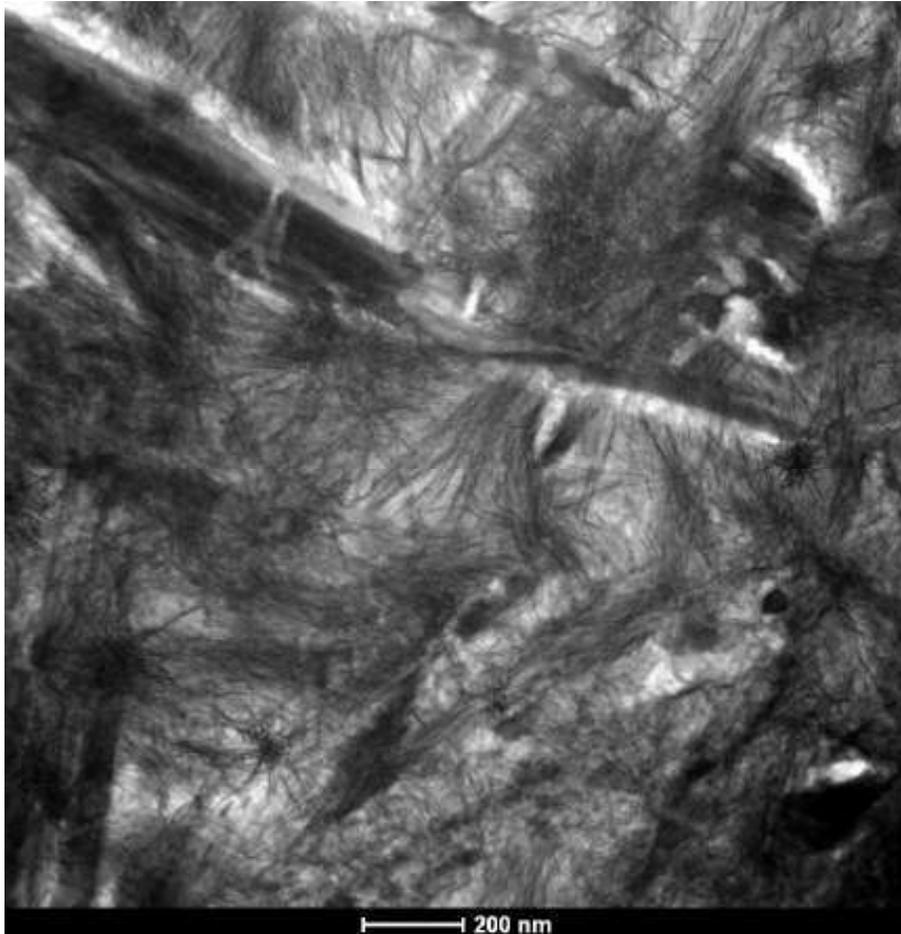


M. Antoni, PhD thesis, EPFL, 2013

## Migration test: summary



- Stadium Model shows an improvement of diffusion coefficient by **factor 10 between PC and LC3-50**



10 nm =  
40 water molecules

~5 layers are  
“structured”  
Mobility of 4<sup>th</sup> layer  
2x less than free water

What about charged  
ions?.

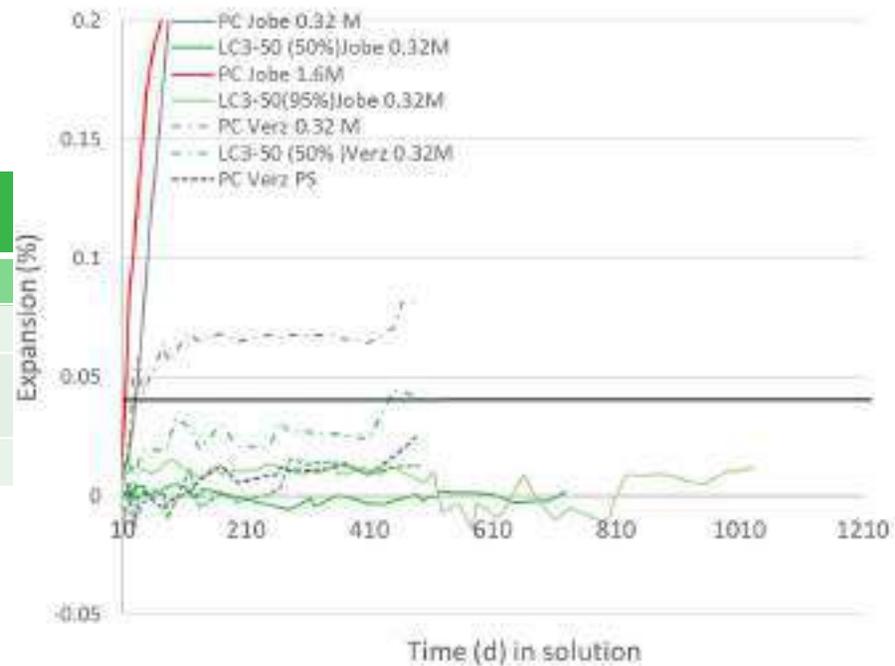
# Alkali Silica Reaction

# ASR

## ➤ Expansion vs time

Jobe (high reactive)		Verzasca (low reactive)	
PC	LC3-50	PC	LC3-50
0.32M	0.32M	0.32M	0.32M
1.6 M		Pore Solution	PS
		1.6M	

-Immersed in solution after 28days curing  
-Stored at 38°C

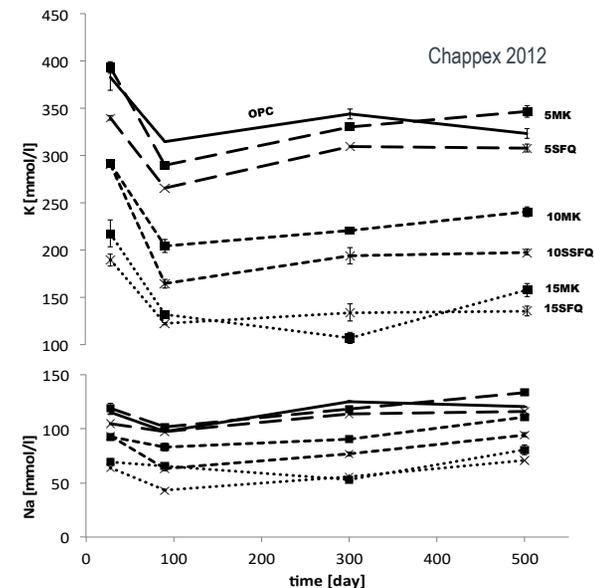


## Impact of alumina silicate SCMs

- SCMs containing silica and alumina are very effective to prevent ASR
- Silica lowers the Ca/Si ratio of the C-S-H by the pozzolanic reaction
- This in turn lowers the pH of the system:

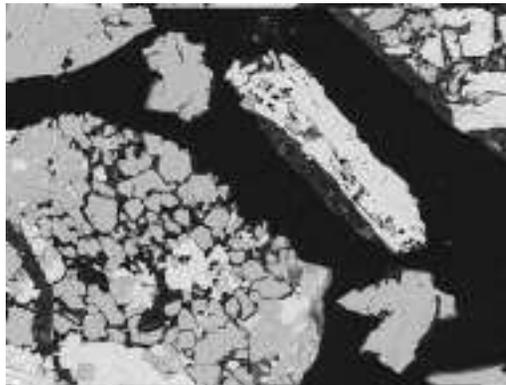
Here we can see that just 15% of metakaolin or silica fume reduces the concentration of alkalis by a factor of 3

But as for low alkali cements this lowering of the pH seems only to delay rather than prevent ASR

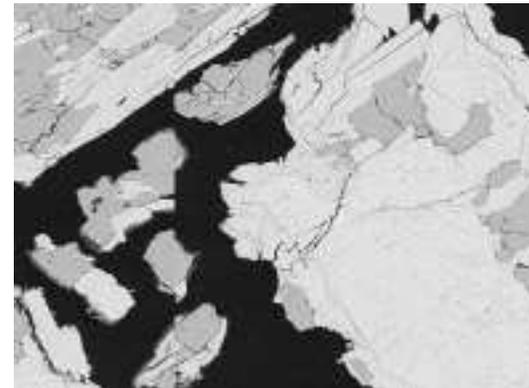


## Impact of alumina rich SCMs

- It has been realised for some time that SCMs containing alumina are more effective
- The work of Chappex at EPFL showed this was because alumina adsorbs on reactive sites of reactive silica and inhibits the dissolution:



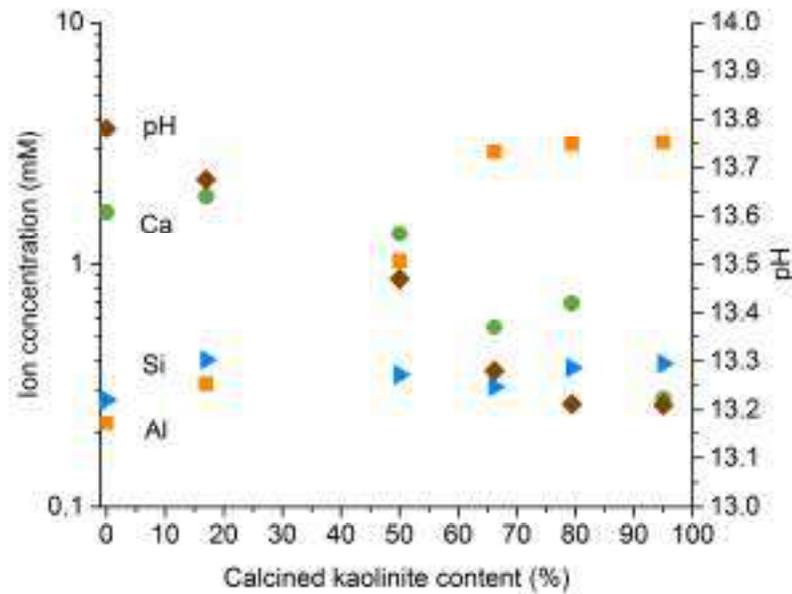
Dissolution of  
aggregates after 1 year  
in alkaline solution, no  
alumina



Dissolution of  
aggregates after 1 year  
in alkaline solution, with  
alumina

Chappex 2012

## Alumina in solution increases with kaolinite content



Pore solution  
compositions  
from LC<sup>3</sup>  
systems

Avet 2017

# Workability

## LC3

- Limestone and calcined clay are both much softer than clinker
- With intergrinding, high blaine and clinker is likely to be underground. But situation can be improved by separate grinding or addition of calcined clay at separator
- However effect of limestone and impurities in clay has positive influence
- Good flowable concrete can be obtained with use of superplasticizers
- In some formulation SP dosage may even be less



## Concluding remarks

- Future cements will be based on Portland cement clinker with increasing levels of incorporation of SCMs
- Calcined clays are the only realistic option for extending the use SCMs
- Workability can be mastered
- Calcined clays have very positive impact on:
  - Chloride ingress
  - ASR
- Possible downside is faster carbonation, but there is a low risk of carbonation induced corrosion in most concrete
- If we are serious about more sustainable concrete we need to use cements with lower CO<sub>2</sub> emissions, e.g LC<sup>3</sup> clinker/ calcined clay / limestone blends

# Thank You