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LABORATORY OF CONSTRUCTION MATERIALS

Advanced cementitious materials, MSE 420

Lecture 10: SCMs and Limestone Calcined Clay Cement (LC3)

Dr. Beatrice Malchiodi
20 November 2024

Course Schedule

Wk #	Class date	Title	Lecturer
1	11/09/2024	Introduction/literature review	Prof. Karen Scrivener /Dr. Alastair Marsh
2	18/09/2024	Durability of cementitious materials	Dr. Beatrice Malchiodi
3	25/09/2024	Cement hydration	Prof. Karen Scrivener
4	02/10/2024	Characterisation techniques for cementiitous materials	Dr. Federica Boscaro
5	09/10/2024	Presentation 1	
6	16/10/2024	Admixtures	Dr. Federica Boscaro
7	30/10/2024	Presentation 2	
8	06/11/2024	LCA - Life Cycle Analysis	Dr. Alastair Marsh
9	13/11/2024	Sustainability approaches for construction	Dr. Alastair Marsh
10	20/11/2024	LC3 - Limestone Calcined Clay Cement	Dr. Beatrice Malchiodi
11	27/11/2024	Concrete design	Dr. Beatrice Malchiodi
12	04/12/2024	Concrete saving through a better structural design / Q&A on Presentation 3	Porf. David Ruggiero
13	11/12/2024	Presentation 3	
14	18/12/2024	08:15-09:00 Precast concrete, Sustainability in Concrete and Building Codes	Prof. David Fernandez-Ordoñez
		09:10-09:50 Circularity: Reuse of concrete elements	Prof. Corentin Fivet
		09:50-10:00 Semester projects at LMC	

Learning objectives

By the end of this class, you will be able to…

- Contextualise the importance of implementing blended cement.
- Define and identify different blended cements.
- Understand how to measure the reactivity of SCMs and evaluate their performance.
- Define the advantages of using LC3 amongst the other available SCMs
- Define the properties and best applications for LC3
- See the historical evolution of LC3 and its real and potential impact

Context: Why studying blended cement?

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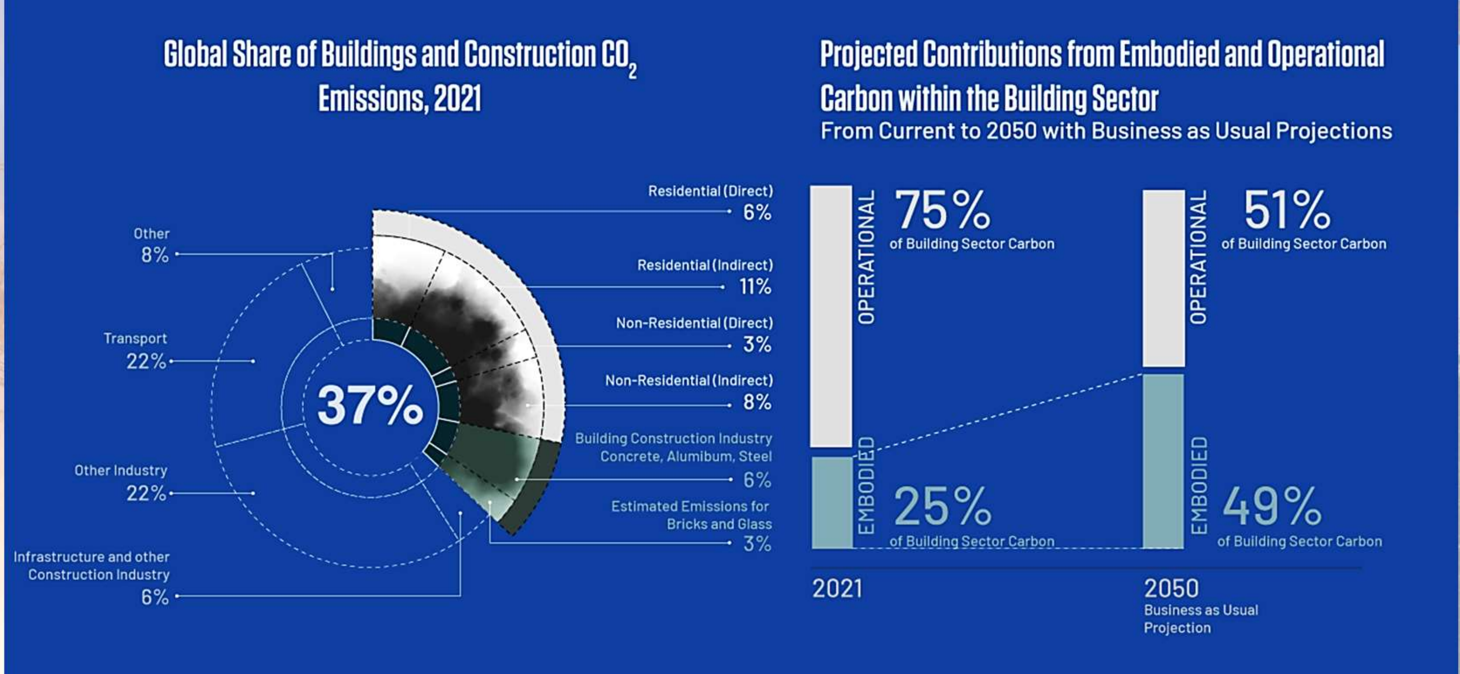
Global CO_2 emissions and the Construction sector



Source: GlobalABC: Sustainable Building Materials Hub

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Sustainable construction is key to achieving net zero

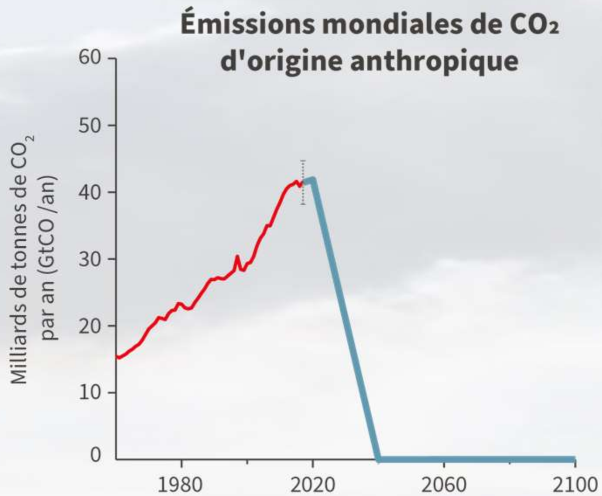
A radical transition is imperative:

Paris Agreement, 2015:
Keep global warming below 2°C, targeting 1.5°C

Actual global warming = 2.4°C

Intergovernmental Panel on Climate Change, 2018 and COP27:
Halving CO_2 emissions by 2030, carbon neutrality by 2050

- Cut CO_2 emission in half in the next 10 years
- Reach net zero in 2050



IPCC. 2019. 1.5°C report

Are there any other alternatives to concrete?

IN PRACTICE

'Over 90% of concrete used in construction could be replaced with timber'

20 JULY 2023 • BY FRAN WILLIAMS

https://www.architectsjournal.co.uk

Original Research Article

I•M3
Institute of Materials, Minerals & Mining

International Wood Products Journal
1–9

DOI: 10.1177/20426445241274848
journals.sagepub.com/home/iwp
Sage

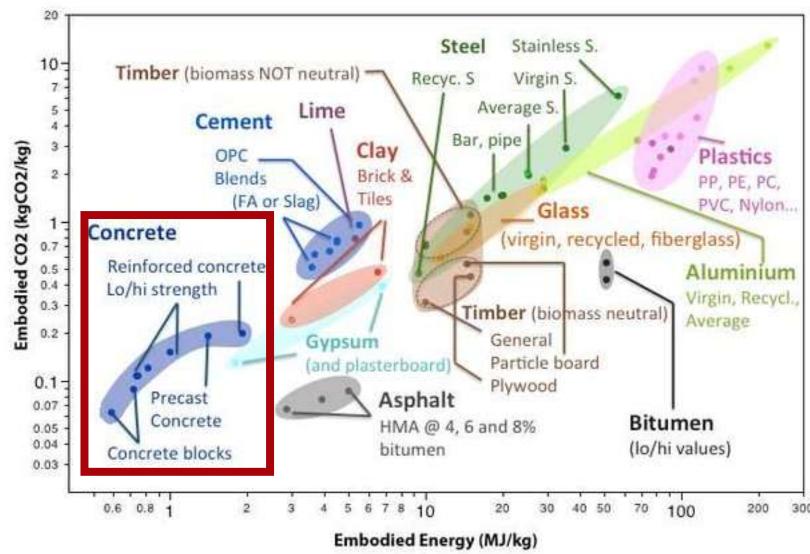
Concrete cracks, wood burns: Competing narratives in the construction sector

Pipiet Larasatie[1], Kathy Young[2] and Eric Hansen[3]

Are there any other alternatives to concrete?

- Among the most efficient building materials in terms of embodied environmental impact and embodied energy

- Outstanding properties i.e.:
  - Easy to manipulate by ow-skilled workers
  - Low cost
  - Robust
  - Durable
  - High strength
  - Different shapes
  - Raw materials are abundant and widely distributed



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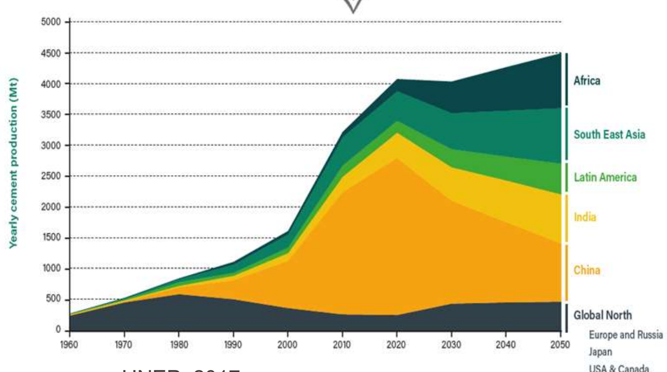
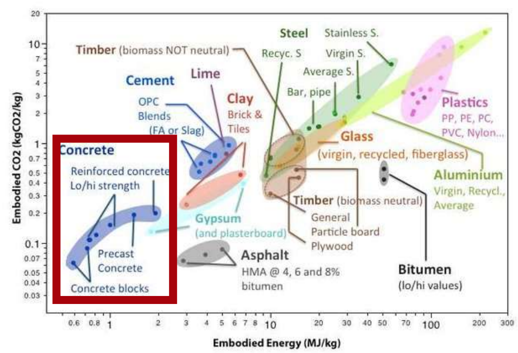
Concrete is an environmental friendly material, but..

We use a lot of it.
The demand for cement will come from Developing economies
Need solutions for people in developing countries

CO_2 emissions (t/y) = (1) yearly production (t/y) × embodied CO_2 (t CO_2/t material) (2)



UNEP, 2017



Our Goal?

Reducing embodied carbon within the building sector by acting at different levels

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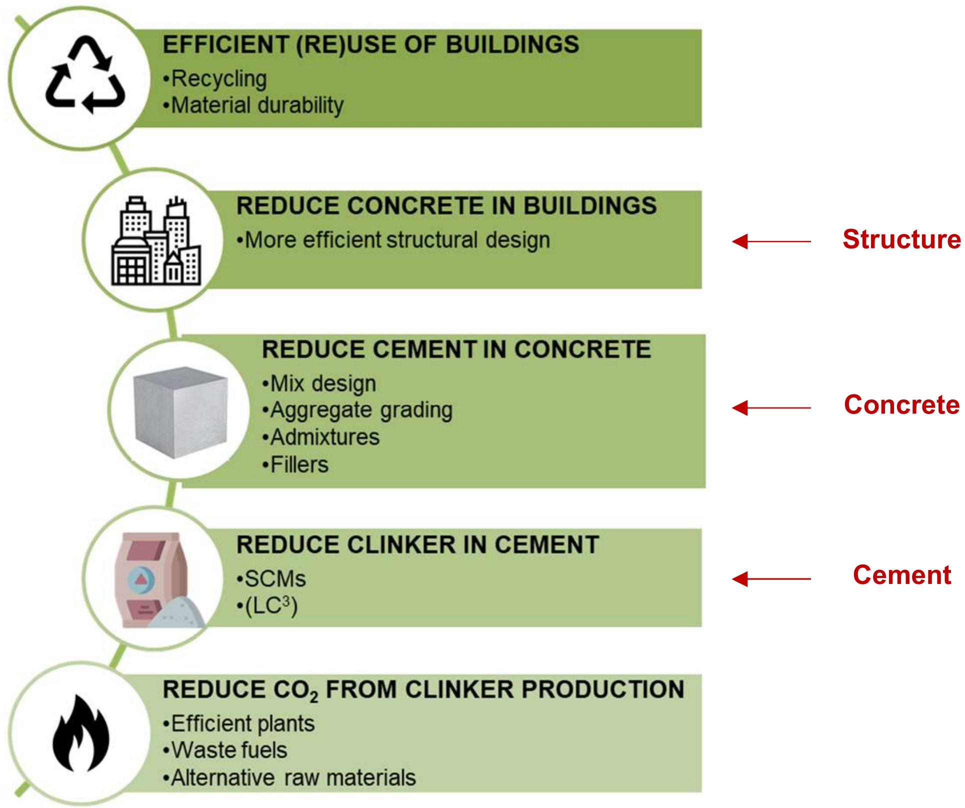
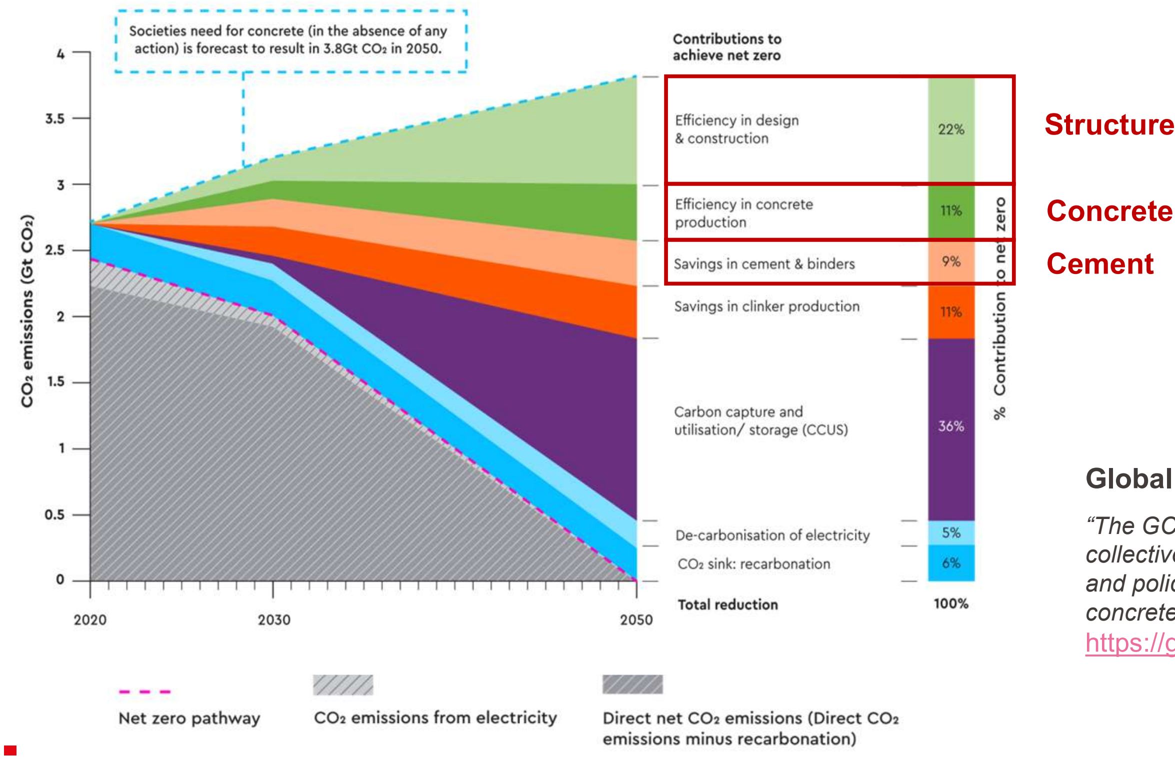
A multidimensional approach

Recommended reading



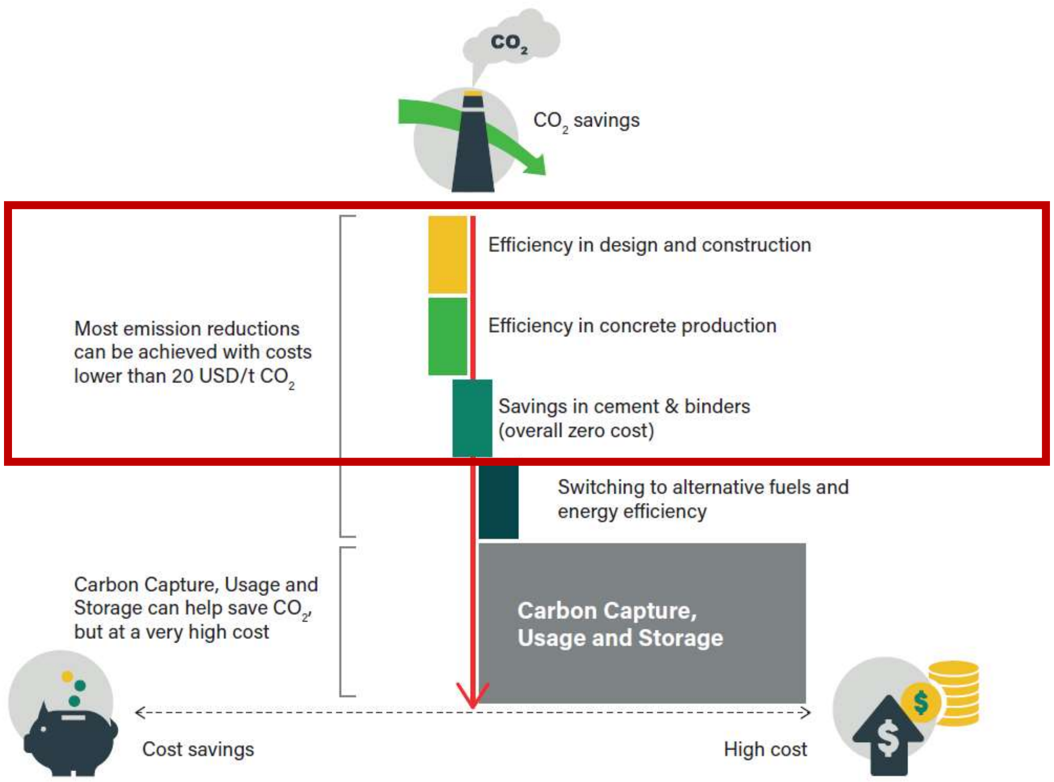
A multidimensional approach – GCCA Roadmap



Global Cement and Concrete Association (GCCA)

"The GCCA 2050 Net Zero Roadmap sets out in detail how collectively, in collaboration with built environment stakeholders and policymakers, we will fully decarbonize the cement and concrete industry and provide ***net zero concrete*** *for the world."*
https://gccassociation.org/concretefuture/

Getting to net zero with little to no cost



GCCA 2021

nature communications

Article
https://doi.org/10.1038/s41467-023-40302-0

Near-term pathways for decarbonizing global concrete production

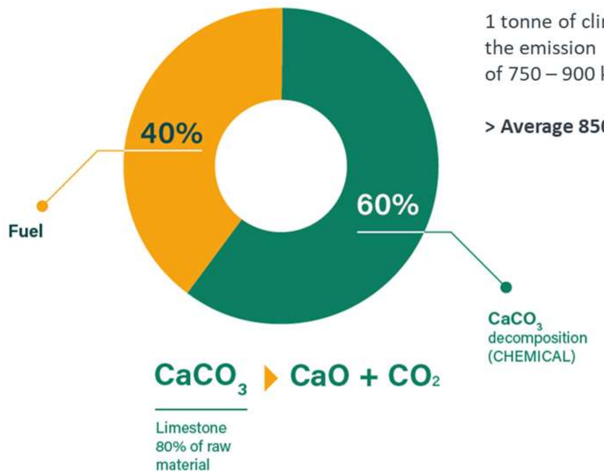
Received: 27 January 2023
Accepted: 21 July 2023

Josefine A. Olsson[1], Sabbie A. Miller[1] & Mark G. Alexander[2]

Calculated **76%** with these strategies

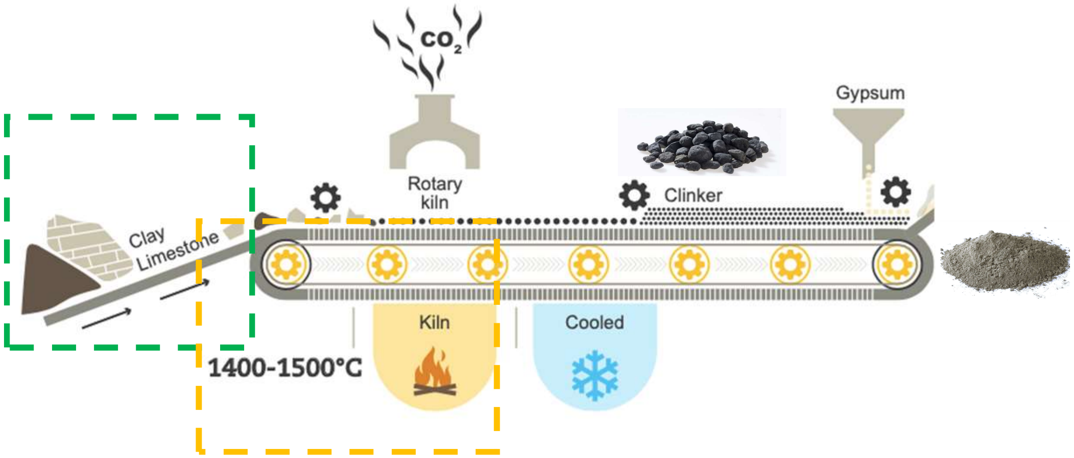
Acting at cement level: SCMs and Blended cements

Origin of CO_2 emission in cement production



1 tonne of clinker leads to the emission of 750 – 900 kg CO_2

> Average 850kg/t



Replacing clinker with SCMs

- Clinker production: Most expansive and highest emissive step in cement production
- Reduction of these impacts using SCMs.

4600
Million of tons of Portland cement
(CEMBUREAU, 2015)

626
Kilograms per capita per year
(UNEP, 2016)

~ 5-8%
Anthropogenic CO_2 emissions
(EPA)

~ 25%
by 2050 if no actions are taken
R. Snellings, Assessing, Understanding and Unlocking Supplementary cementitious materials. RILEM TL, 2016

SCMs: definition

Supplementary Cementitious materials (SCMs) are a group of materials that show hydraulic or pozzolanic behavior.

Hydraulic material: material that can set and harden sub-merged in water by forming cementitious products in a hydration reaction.

Pozzolan material: Defined by ASTM C618 as a siliceous or siliceous and aluminous material which, in itself, possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, react chemically with calcium hydroxide (lime) at ordinary temperature to form compounds possessing cementitious properties (Mehta 1987).
A quantification of this capability is comprised in the term pozzolanic activity.

R. Snellings, et al. Supplementary cementitious materials. Reviews in mineralogy and geochemistry, 2012

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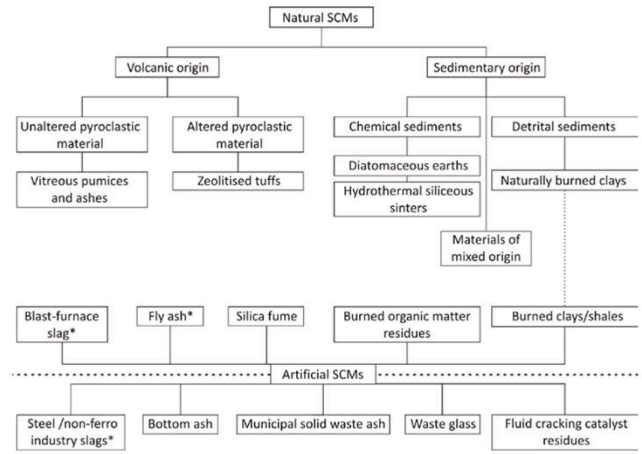
SCMs: types

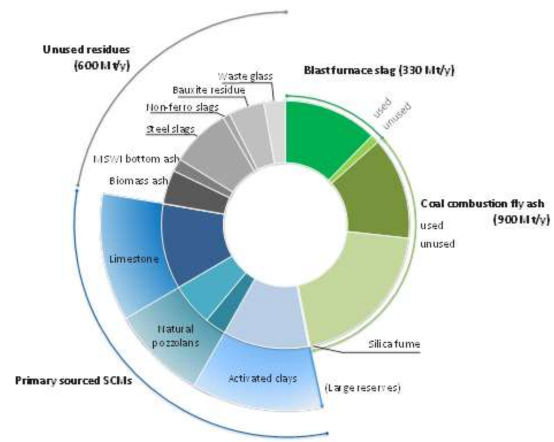


R. Snellings, et al. Supplementary cementitious materials. Reviews in mineralogy and geochemistry, 2012

Classifications in terms of:
- chemical and mineralogical composition
- typical particle characteristic
- reactivity or performance
- **Origin**

1. **Natural origin**
2. **Artificial origin**

   undergone structural modifications as a consequence of manufacturing or production processes.
   Thermal activation of kaolin-clays, or waste or by-products from high temperature processes such as blast furnace slags, fly ashes or silica fume



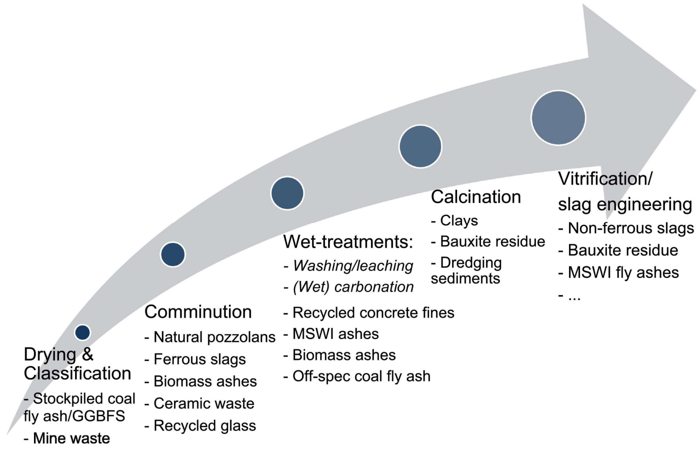
R. Snellings, et al. Assessing, Understanding and Unlocking Supplementary cementitious materials. RILEM Technical letters, 2016

SCMs: production

Beneficiation processing needed to enhance performance and/or to remove deleterious components.

Different techniques used to obtain SCMs, arranged in order of increasing process energy intensity and associated cost.

- Simple and relatively inexpensive: drying, crushing, milling, screening, or size classification,
- More energy- and chemical-intensive: acid treatments, hydrothermal processing, and mineral carbonation treatments,
- Calcination and high-temperature remelting or vitrification.



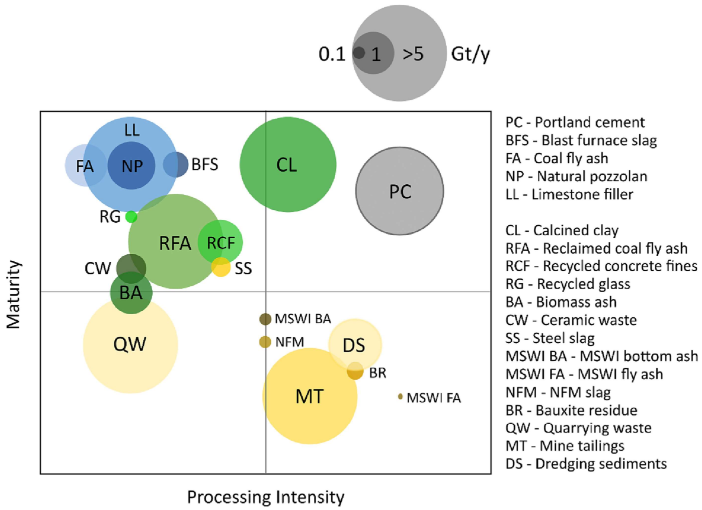
R. Snellings, et al. Future and emerging supplementary cementitious materials. CCR, 2023

SCMs: maturity vs process intensity

All current, emerging and future SCMs are compared in terms of:
- available reserves or supply volumes (circle areas),
- Maturity
- Beneficiation processing intensity

Upper left corner: widely used SCMs that require relatively modest processing.
Lower right corner: early stages of development or far from the market and require (energy-)intensive processing before being suitable for use as SCM.

Techno-economic feasibility and environmental impact analyses are necessary for each process to assess its viability. Research and development efforts are required for some of these processes before they can become industrially scalable.



R. Snellings, et al. Future and emerging supplementary cementitious materials. CCR, 2023

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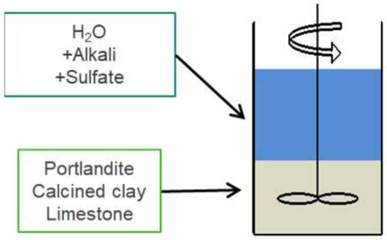
Monitoring reactivity: R^3 test

- Rapid, Relevant and Reliable (R^3). ASTM C1897-20
- Other screening tests already existing, but difficult to correlate results with compressive strength
- **Focus on pozzolanic / synergetic reaction only:** Adjustment of sulfate and alkali content to reproduce the reaction environment of hydrating blended cements



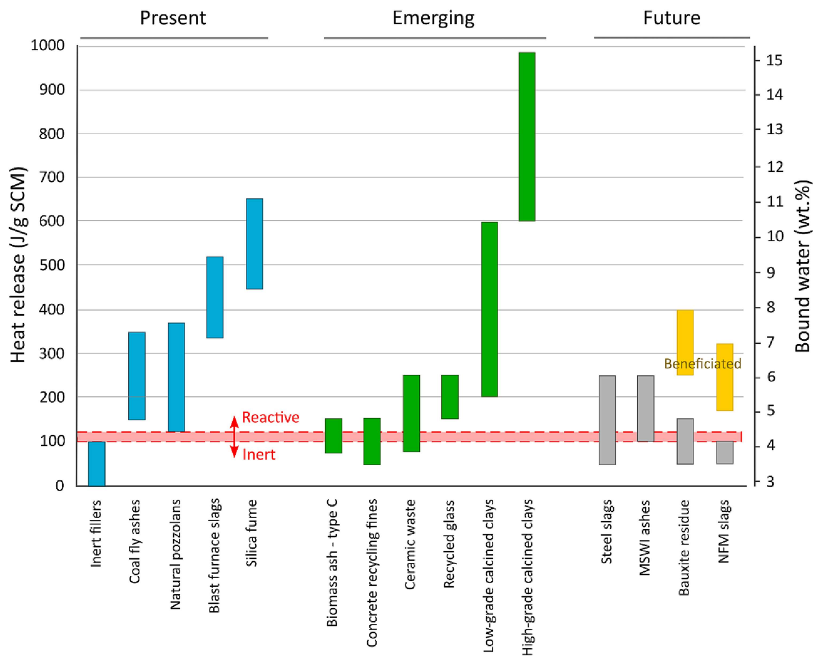
<u>Two ways of measuring the reactivity</u>

Isothermal calorimetry at 40°C Heat release 24h

Oven thermal treatment at 400°C Bound water 3 days

SCMs: reactivity

- SCMs do not perform the same.
- Current, emerging and future SCMs display different Heat release.
- **Heat release - Reactivity – Clinker replacement potential**

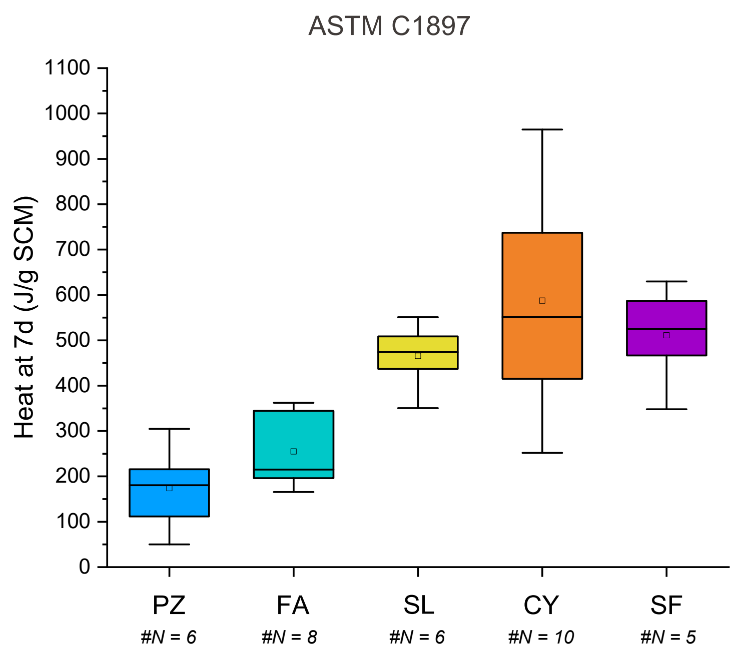


R. Snellings, et al. Future and emerging supplementary cementitious materials. CCR, 2023

Calcined clays vs. other SCMs

Kaolinitic clay with the lowest kaolinite content is more reactive than most pozzolans commonly used in the industry.

Higher reactivity – Higher clinker replacement potential!



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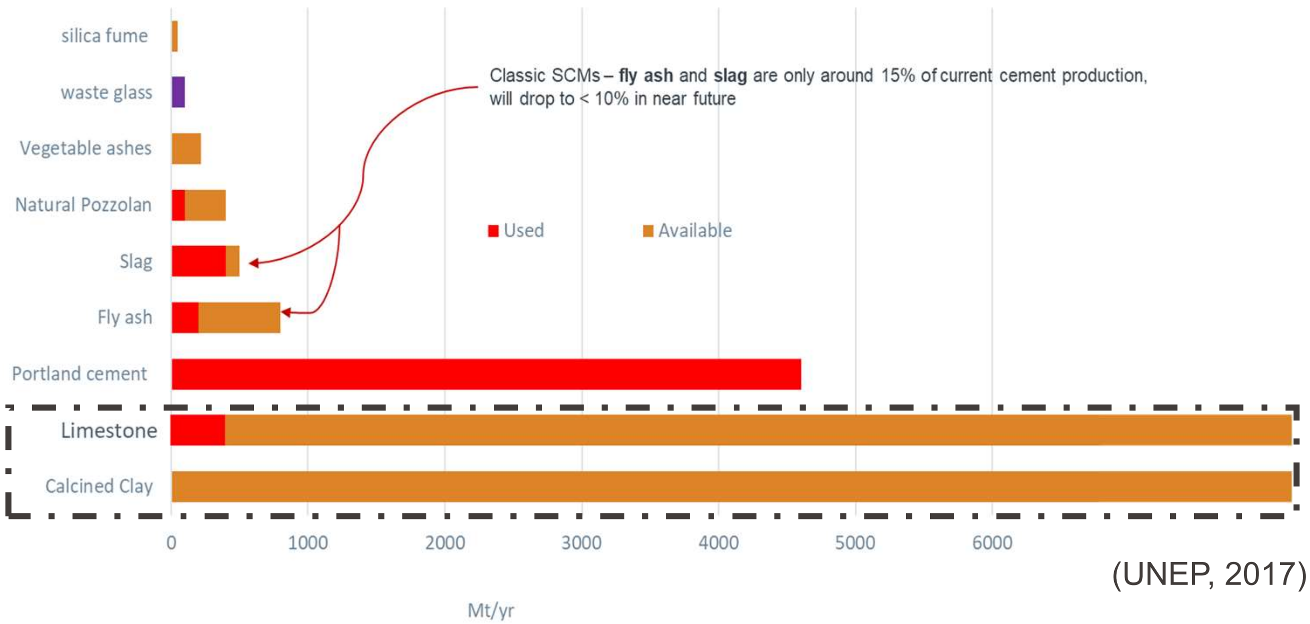
SCMs: Scalability



(UNEP, 2017)

Limestone and calcined clay are the **only SCMs able to replace clinker at scale.**

Limited supply of common SCMs

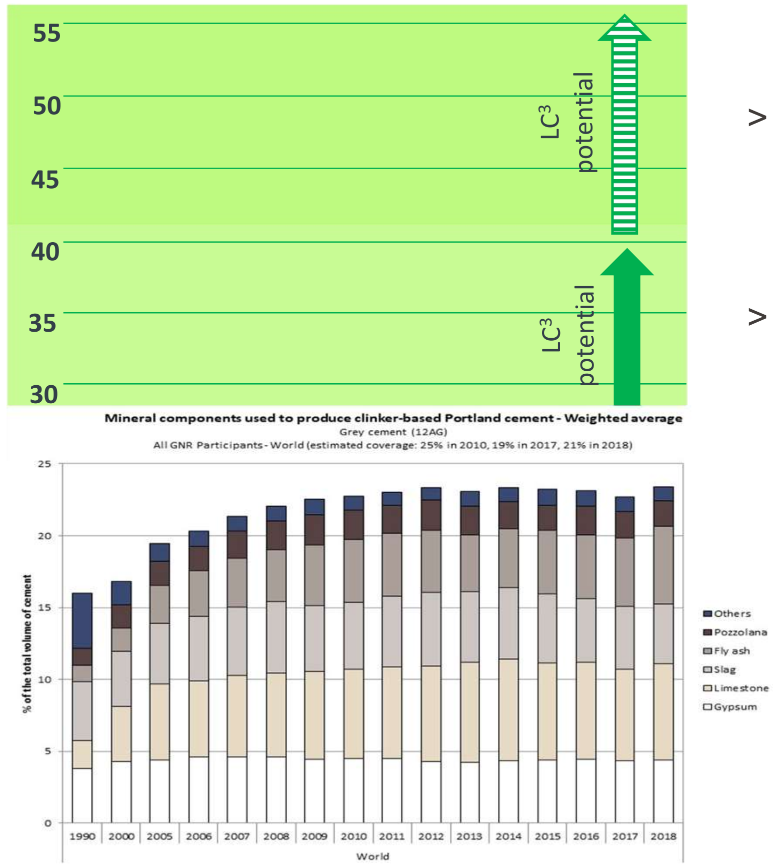
UN environment

Karen Scrivener, EPFL, Switzerland
Vanderley John, USP, Brazil
Ellis Gartner, Imperial College, UK

Can be downloaded for free at multiple sites.

Eco-efficient cements:
Potential economically viable solutions for a low-CO_2 cement-based materials industry

Calcined Clay: only SCM which can expand substitution



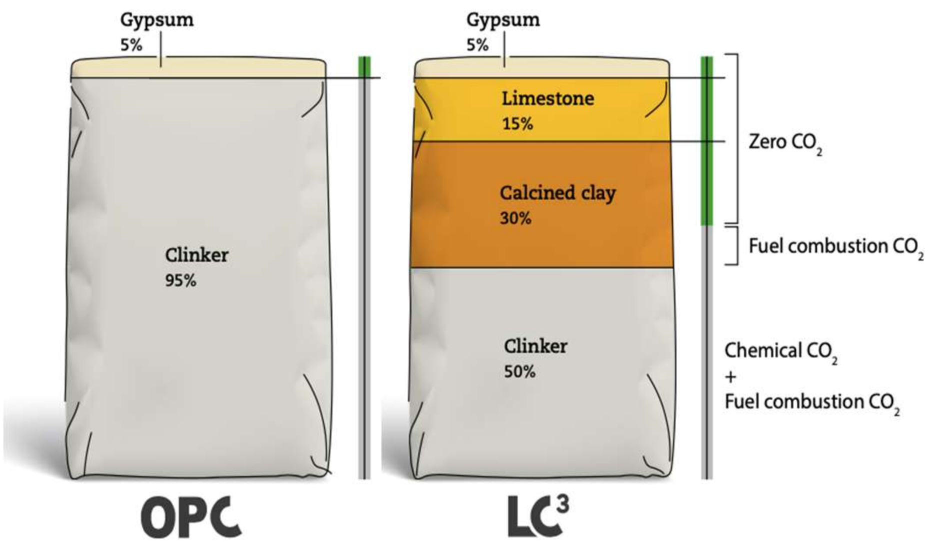
> 800 million Tonnes CO_2/yr

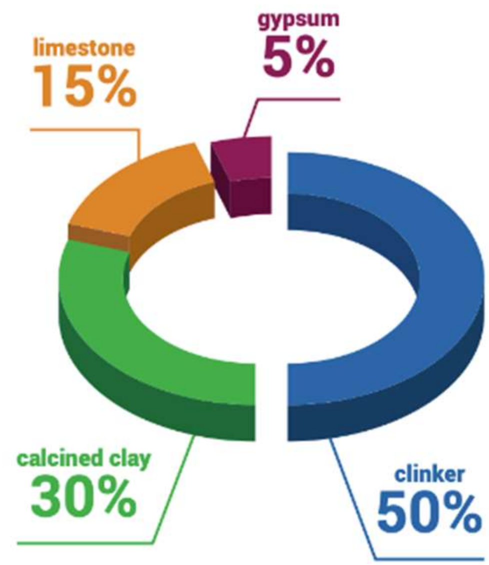
> 400 million Tonnes CO_2/yr

Limestone Calcined Clay Cement (LC^3)

- **What is LC^3?**
- **Advantages**
- Properties
- History
- Applications
- More

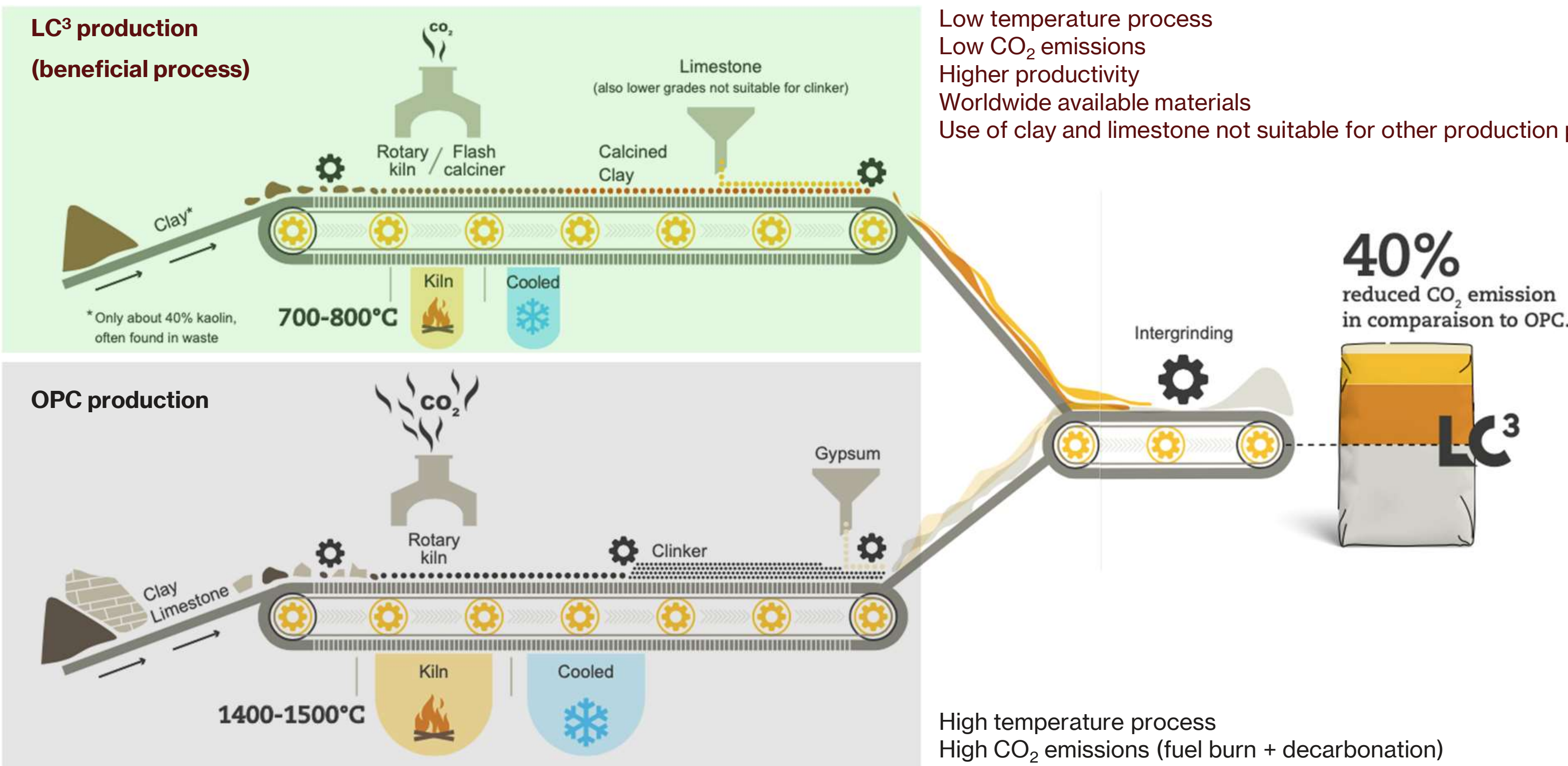
LC^3 - 50





LC^3 is a family of ternary blends

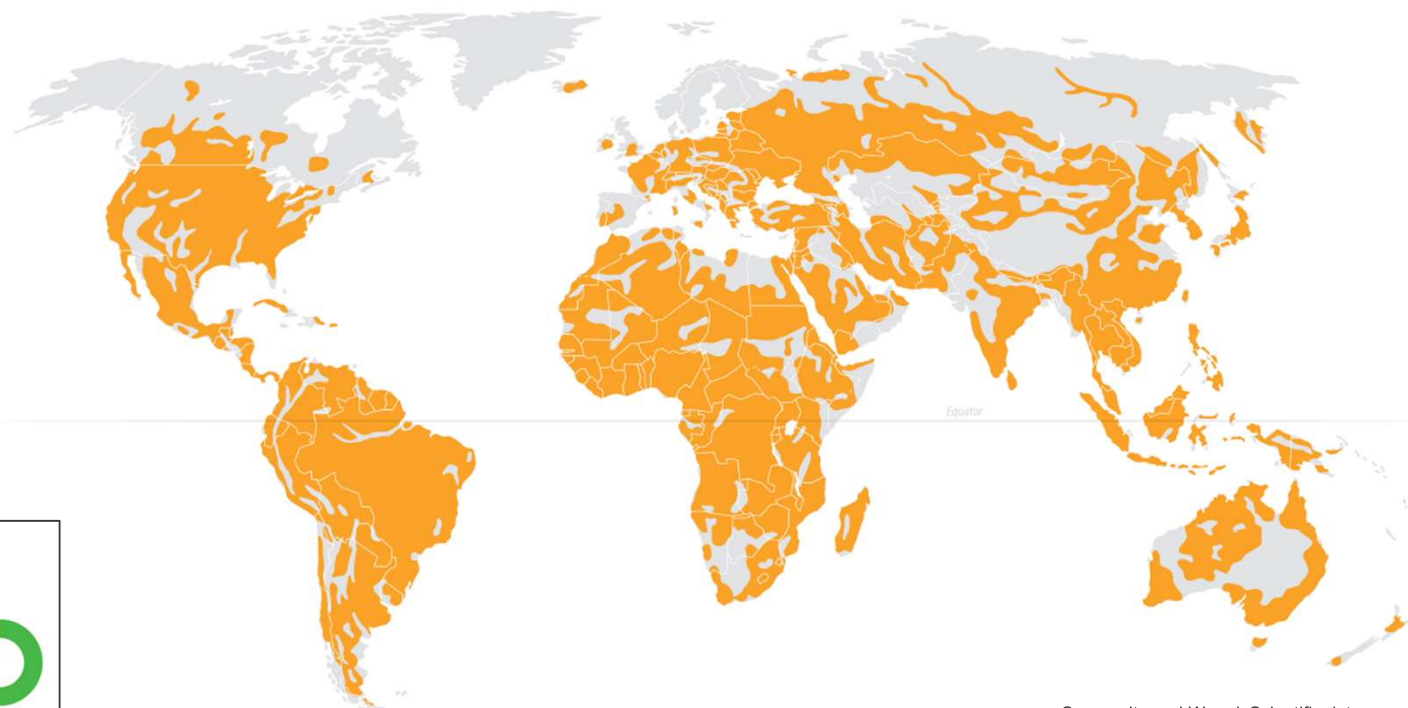
LC^3 - Production process



Low temperature process
Low CO_2 emissions
Higher productivity
Worldwide available materials
Use of clay and limestone not suitable for other production processes

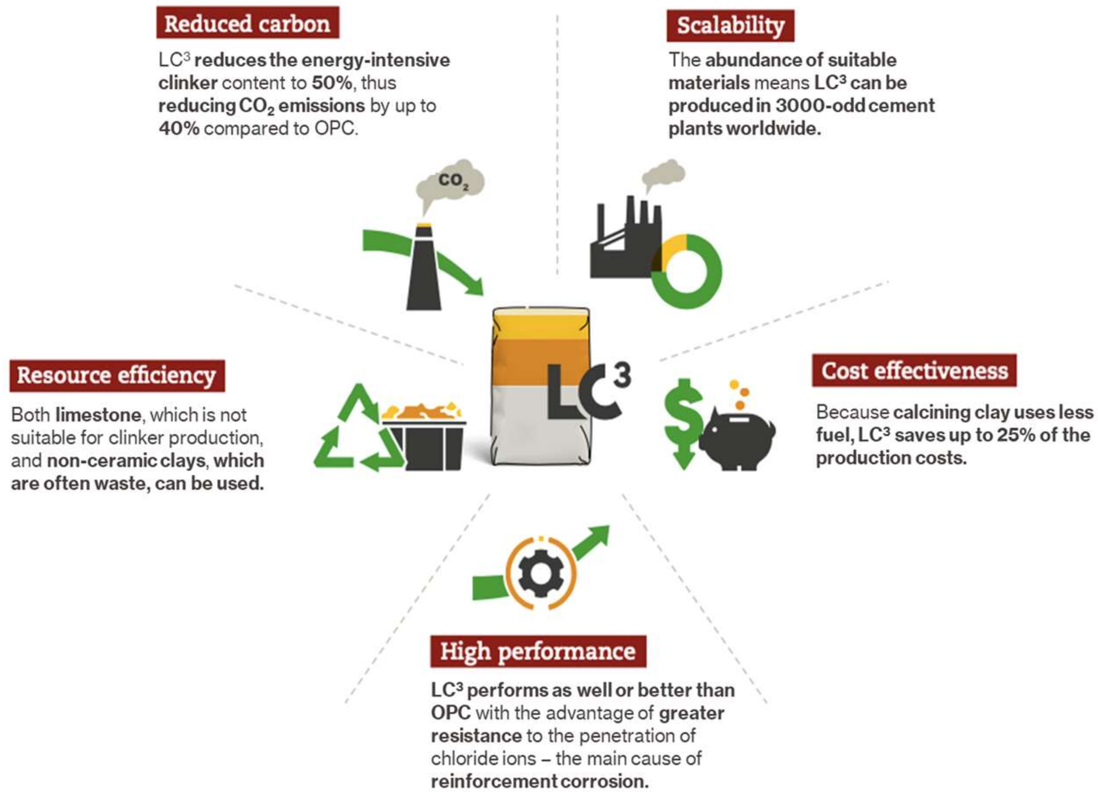
High temperature process
High CO_2 emissions (fuel burn + decarbonation)

World distribution of kaolinitic clays



Source: Ito and Wagai, Scientific data 2017

LC³ - Advantages



LC³ – Sustainable Development Goals

Partnerships for the goals
Fostering partnerships between academia, politics and industry

Climate action
Reducing greenhouse gas emission

Responsible consumption and production
Promoting the utilisation of waste materials and the efficient use of natural resources

No poverty
Promoting affordable housing materials

Industry, innovation and infrastructure
Promoting low-carbon materials for infrastructure and housing

Sustainable cities and communities
Promoting resource efficient cities and the use of local materials

SUSTAINABLE DEVELOPMENT GOALS

Limestone Calcined Clay Cement (LC^3)

- What is LC^3?
- Advantages
- **Properties**
- History
- Applications
- More

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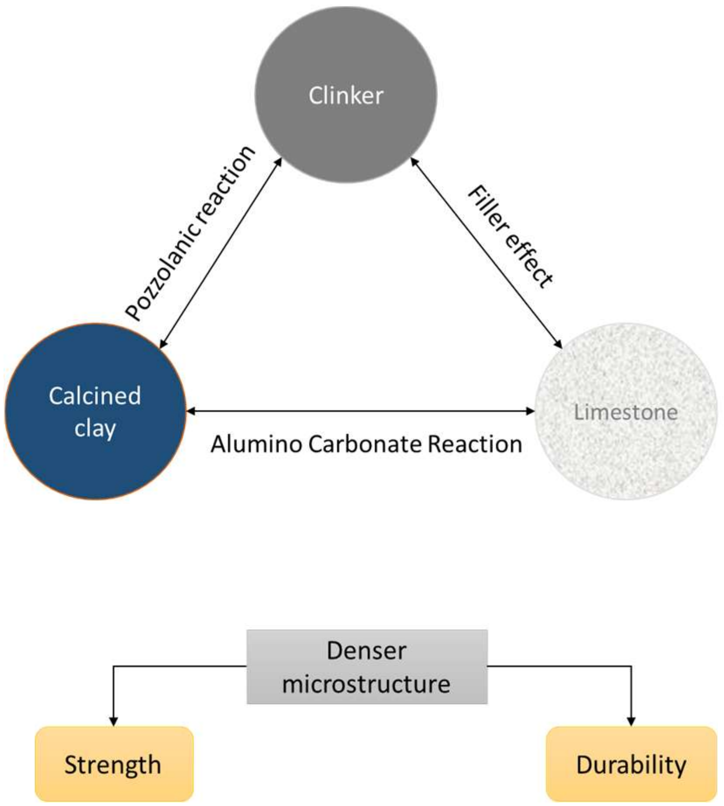
The science behind LC^3

Ternary blend.
The **synergy** between calcined clay and limestone enables higher Clinker substitution levels

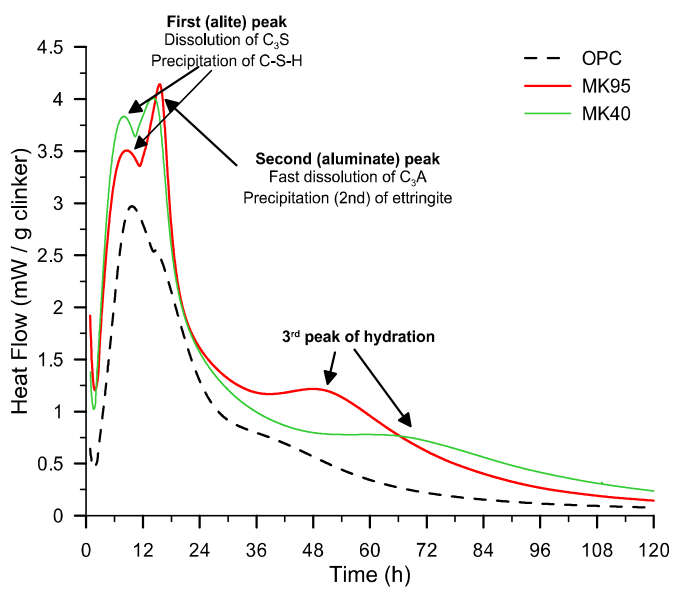
3 reactions:

- Pozzolanic reaction
  (Clinker-Calcined Clays)
- Filler effect
  (Clinker-Limestone)
- Alumino Carbonate Reaction
  (Calcined clays-Limestone)

Bring to pore refinement. Densification of the microstructure leading to improved strength and durability



Reactivity overview of LC^3



Calcined clay (metakaolin)

$$AS_2 + 3CH + 6H \rightarrow C\text{-}A\text{-}S\text{-}H + C_2ASH_8$$

metakaolin → strätlingite

Limestone reaction with clinker aluminates

$$C_3A + Cc + 11H \rightarrow C_4AcH_{11}$$

limestone → monocarboaluminate

$$C_3A + 0.5Cc + 0.5CH + 11.5H \rightarrow C_4Ac_{0.5}H_{12}$$

limestone → hemicarboaluminate

Limestone reaction with aluminates from calcined clay (Synergetic effect in LC^3)

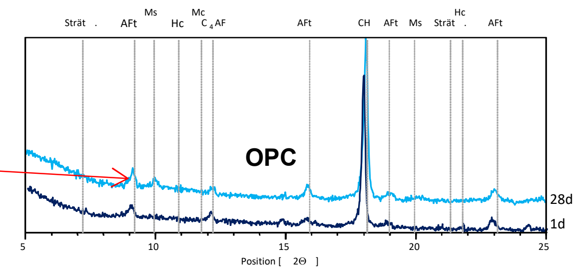
$$AS_2 + 0.5Cc + 3.5CH + 8.5H \rightarrow C_4Ac_{0.5}H_{12}$$

metakaolin → hemicarboaluminate

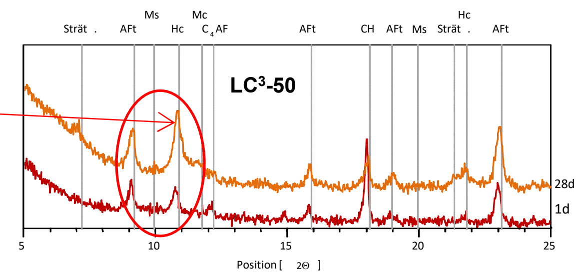
Reactivity overview of LC^3

Results X-Ray Diffraction:

- OPC contains
  - low ettringite (AFt),
  - low monosulfoaluminate (Ms)
  - High Portlandite (CH)



- In LC^3-50:
  - Formation of carboaluminates (Hc/Mc)
  - Ettringite (AFt) enhanced
  - Portlandite is consumed



The combination of calcined clay and limestone favors precipitation of Afm phases (carboaluminates), and stabilize Aft (ettringite)

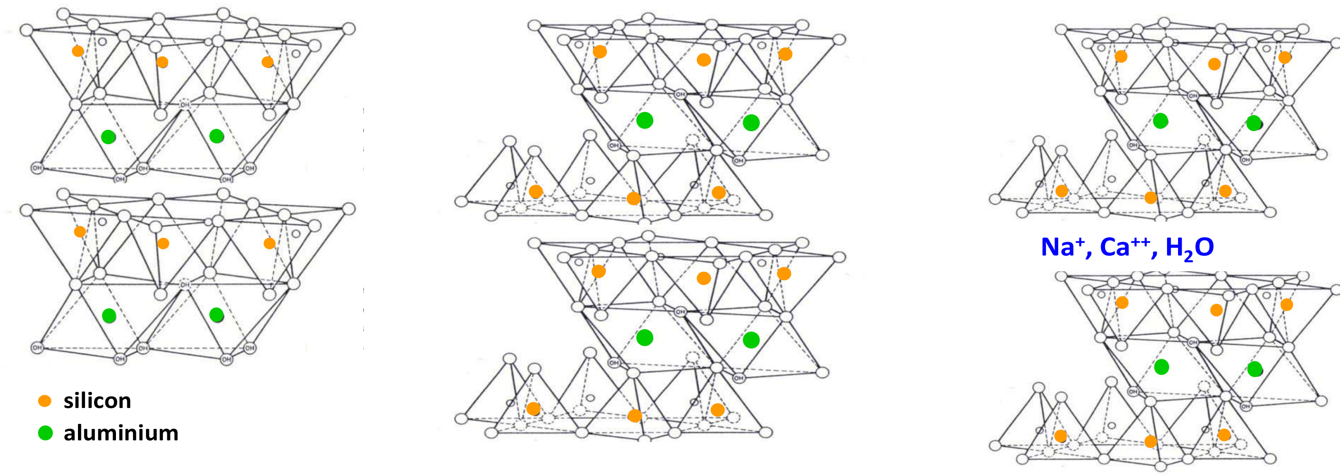
Slide Prof. Karen Scrivener

Which clays are suitable for LC^3

Highest pozzolanic potential for kaolinitic clays

Antoni (2012)
Fernandez (2011)

Kaolinite (1:1) | Illite (Micas) (2:1) | Montmorillonite (Smectites) (2:1)



- Kaolinite
  - Higher amount of hydroxyl groups
  - Hydroxyl groups at the edge of the structural layer
  - More disorder favored during calcination

Calcination

Kaolinite → Metakaolin

AS_2H_2 → AS_2 +2H

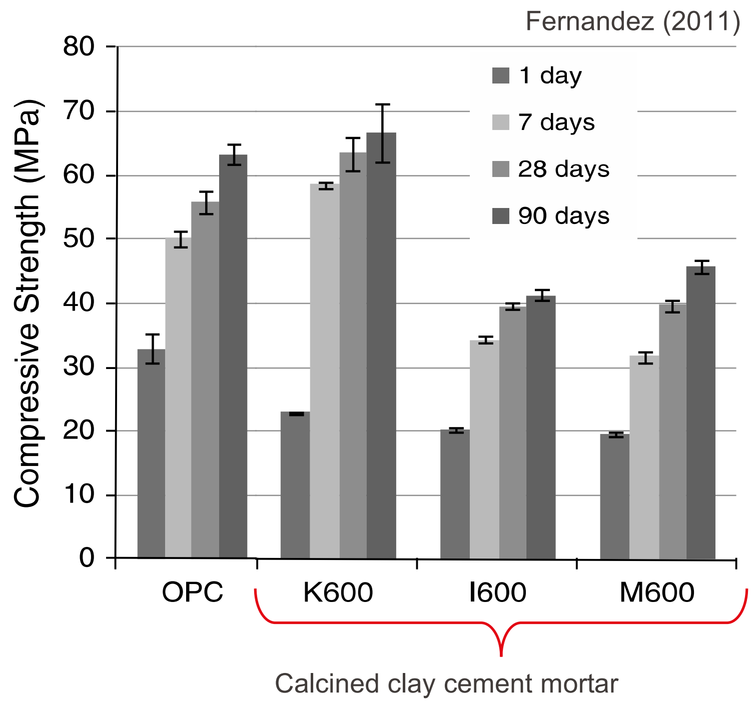
Which clays are suitable for LC^3

Calcination

Kaolinite → Metakaolin

AS_2H_2 → AS_2 +2H

- Calcined clay cement mortars: comparison between calcined kaolinite, illite and montmorillonite
- Much higher strengths obtained for calcined kaolinite blend



Which clays are suitable for LC^3

- We do not need pure kaolinitic clays!
  Already used by other industries

- How does the kaolinite content of clay influence the properties of LC^3 blends?

0% of kaolinite | 50% of kaolinite | 100% of kaolinite

Kaolinite content in clay (%)

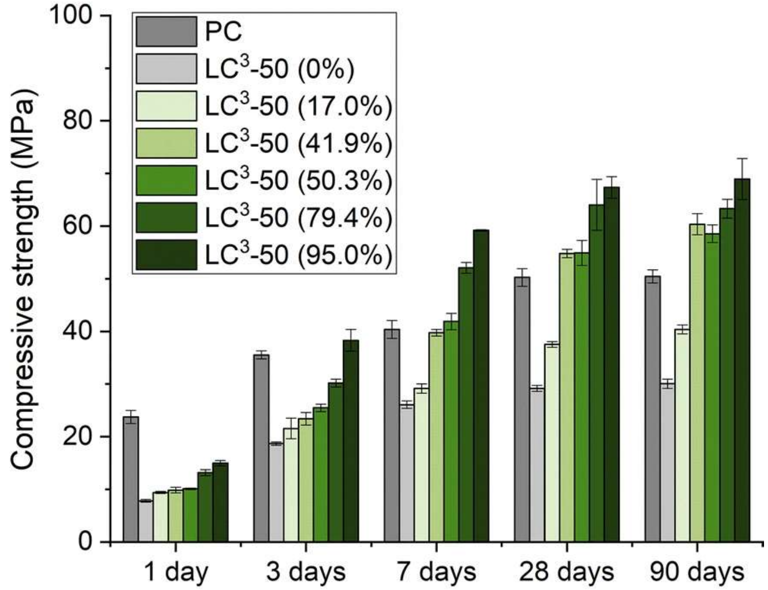
Might not be reactive enough

Clays stockpiled as wastes.
Not used by any other industries.
Potential for LC^3

Used by paper, ceramics, cosmetics

Which clays are suitable for LC^3

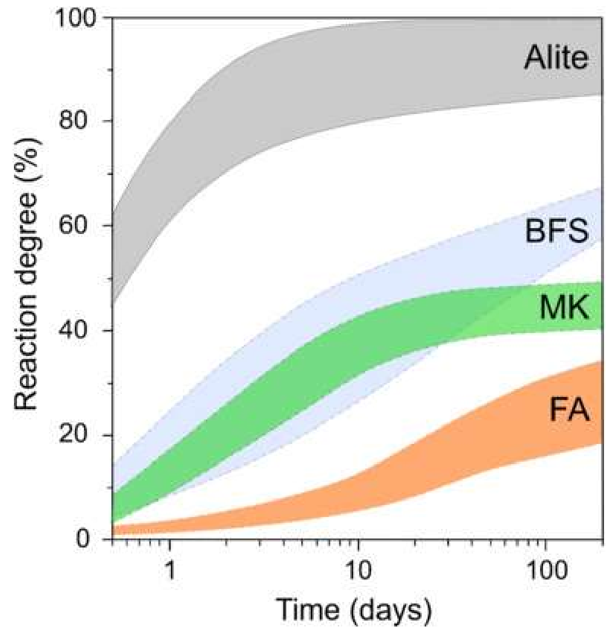
- Strength is the ultimate criteria
- Goal: having comparable compressive strength performance to OPC
- LC^3 50 performs equally to OPC starting already at 7days if 50% kaolinitic clays are used
- Higher kaolinitic content clays allow reaching OPC's compressive strength at 3 days
- Blending clays could enable a good use of resources, yet fulfilling target properties



H. Maraghechi et al. Performance of Limestone Calcined clay cemente (LC3) with various kaolinite contents with respect to chloride transportFernandez (2011), Materials and Structures, 2018

Strength development

- Lower strength developments
- The pozzolanic reaction happens at a deferred time



J. Skibsted et al. Reactivity of supplementary cementitious materials,CCR, 2019

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Selecting and Testing clay

Sampling
- Existing data
- Establish a grid

Kaolinite content
- TG vs XRD

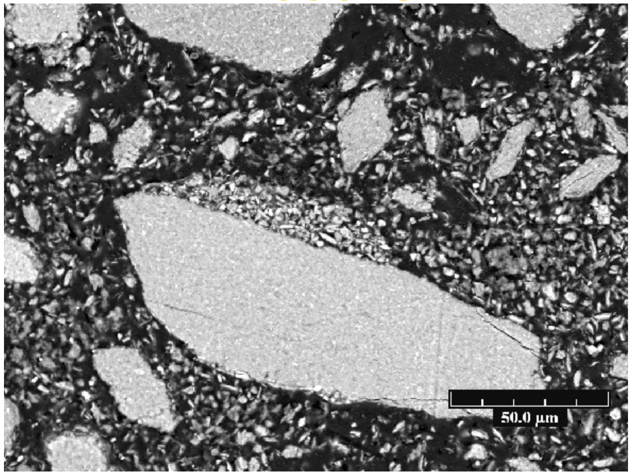
Reactivity
- R3 protocol
- Other protocols

ASTM INTERNATIONAL

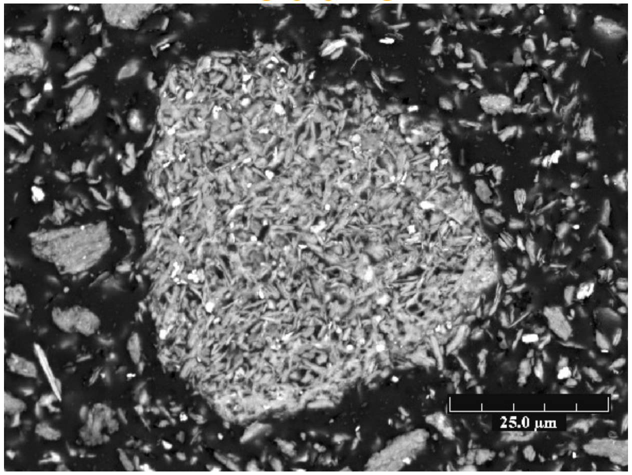
Designation: C1897 – 20

Calcination temperature

600°C

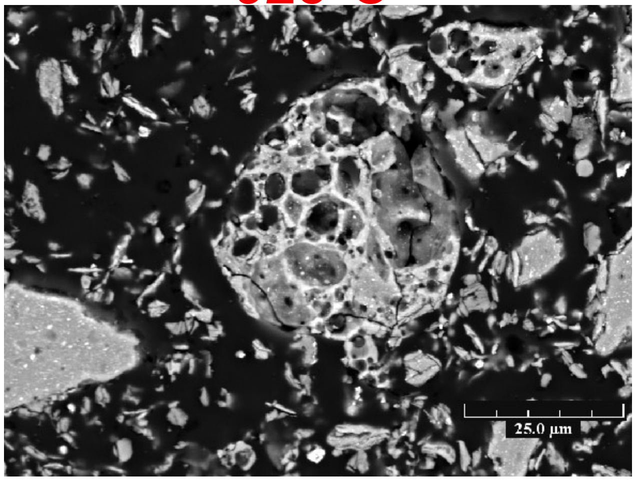


800°C



Small clay plates may agglomerate

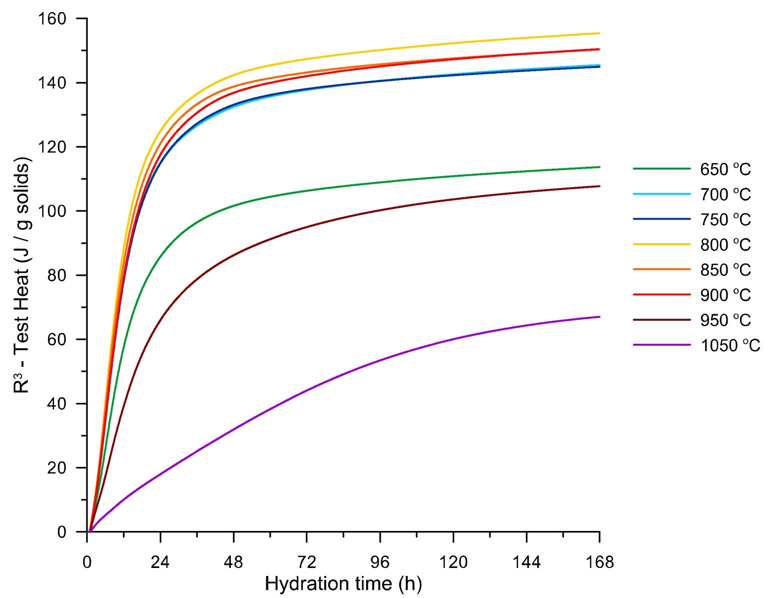
925°C



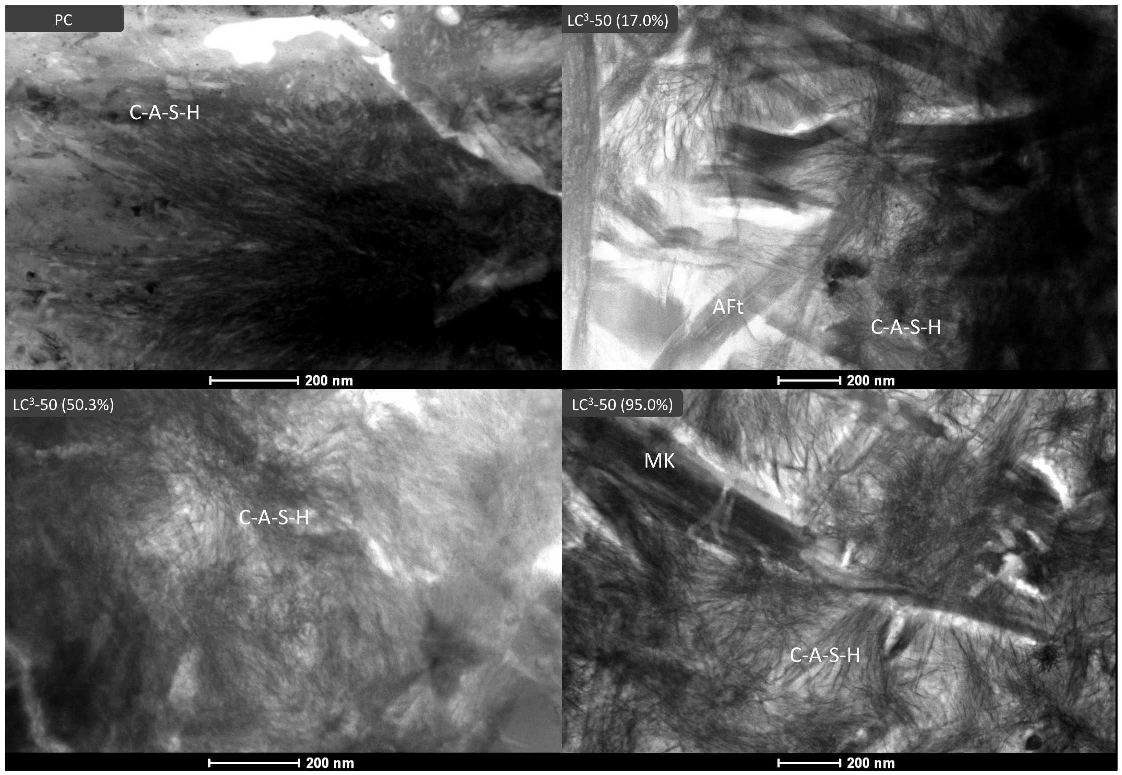
Higher temps, some sintering, decrease of specific surface, decrease of reactivity

Calcination temperature

- Optimal calcination range typically between 700 and 800°C

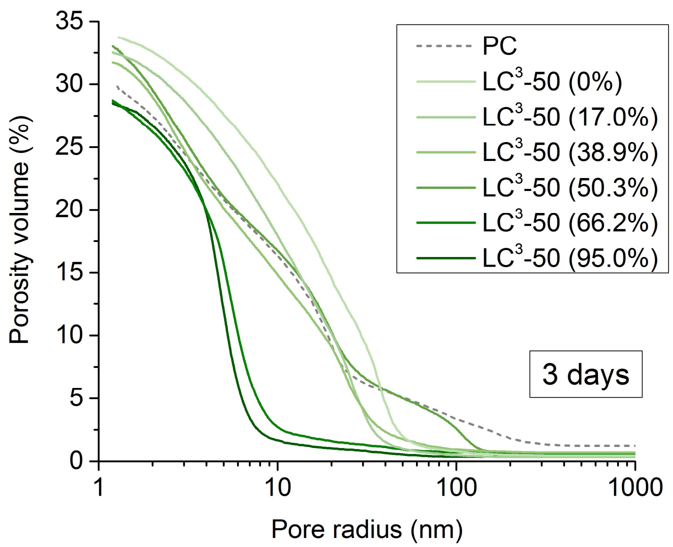


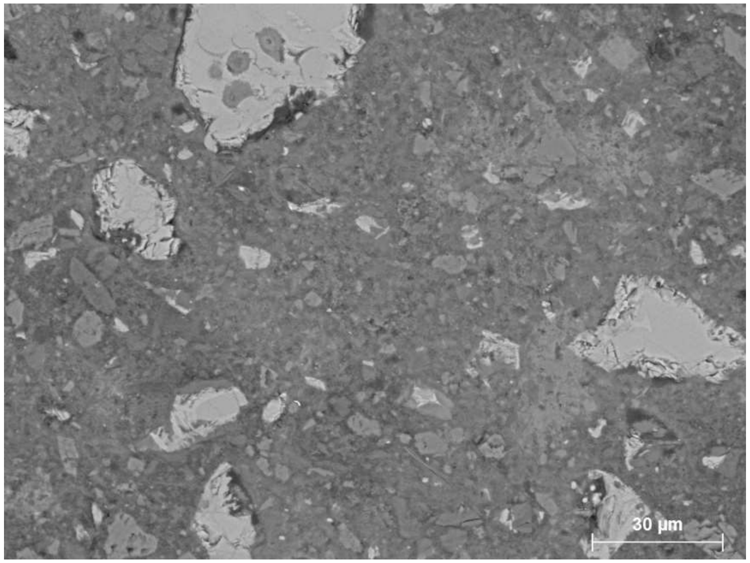
C-A-S-H Morphology



Porosity refinement

Porosity characterization by MIP: Significant refinement of porosity already at 3 days of hydration



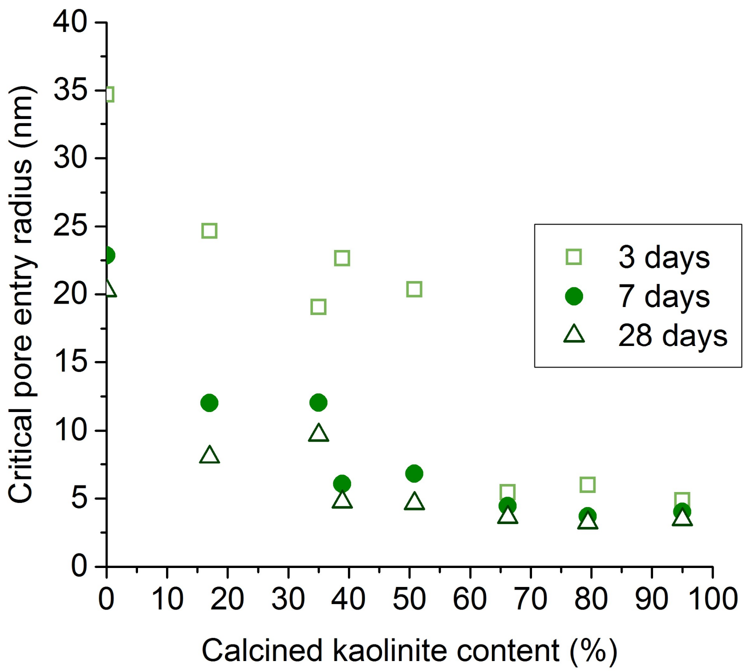


- Porosity well defined at 3 days for high-grade calcined clays
- Kinetics depending on the grade of calcined clays

H. Maraghechi et al. Performance of Limestone Calcined clay cemente (LC3) with various kaolinite contents with respect to chloride transportFernandez (2011), Materials and Structures, 2018

Porosity refinement

- Different kinetics of refinement of porosity
- Porosity already well defined at 3 days for high-grade calcined clays
- Slower refinement for blends with lower kaolinite content
- Limit critical pore entry radius reached for blends with calcined kaolinite content ≥40%



H. Maraghechi et al. Performance of Limestone Calcined clay cemente (LC3) with various kaolinite contents with respect to chloride transportFernandez (2011), Materials and Structures, 2018

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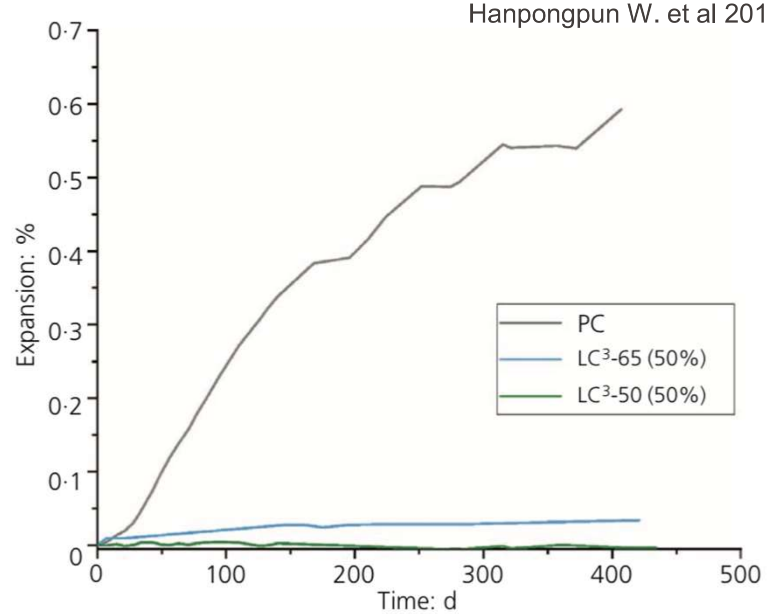
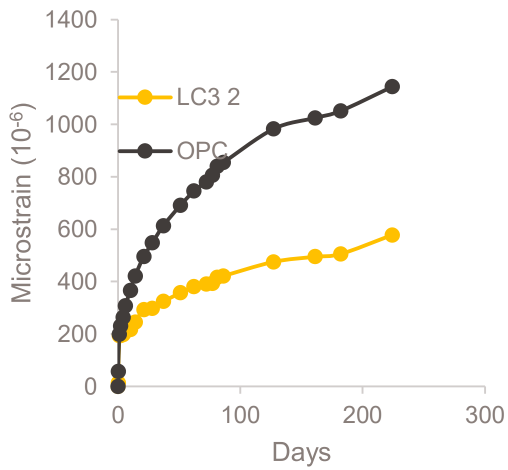
Alkali Silicate Reaction (ASR)

Scrivener K., Avet F., Hanpongpun W. et al 2018

- Avoid reactive aggregates
- Use cement with low alkali content
- Add SCMs (calcined clays, fly ash etc.)
- Add air to compensate for stresses



Much reduced creep

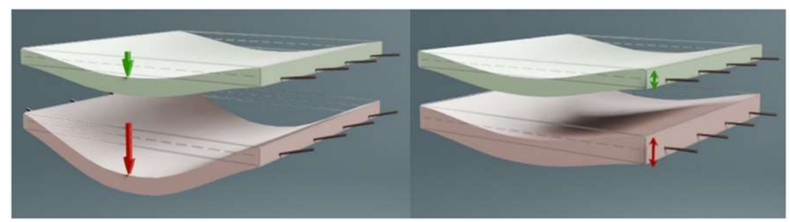


50% creep reduction

ADVANTAGES:

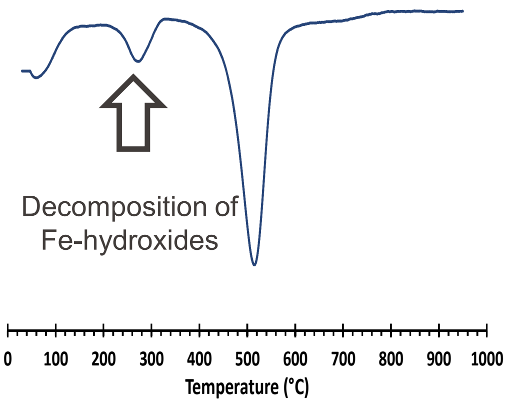
Lower deflection (longer service life)

Thinner cross section (material saving)



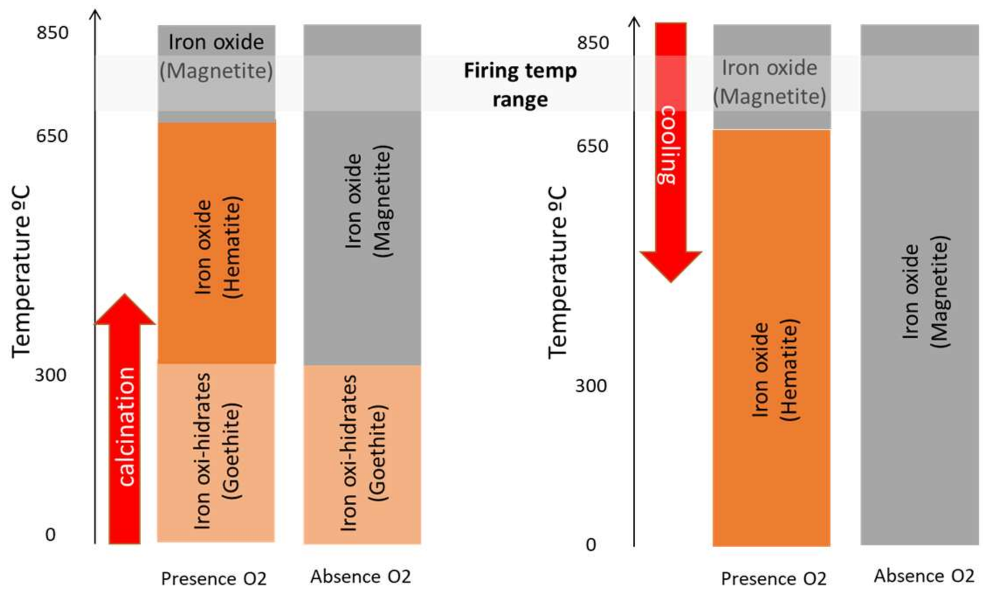
LC^3 - Colour control

LC[3] - Colour control



In the firing chamber due to combustion and the high temperature (T≥ 600ºC) formation of magnetite prevails

However, during cooling, if the material reaches 600ºC and below in a O2 rich environment, hematite can form again



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LC^3 - Colour control at a pilot plant

Exhaustion of oxygen is done by inserting a liquid fuel lance at the cooler. Combustion of the fuel (approximately 0.5% increase in fuel) can do this quickly and safely.

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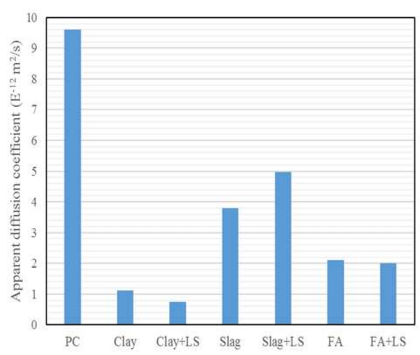
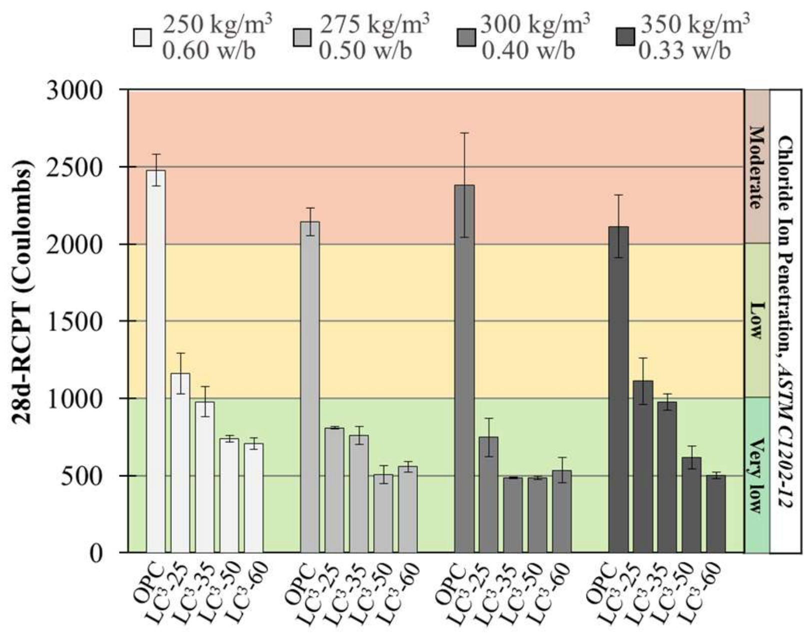
Rapid Chloride Ion Penetration (RCPT)

According to ASTM benchmark:

- **OPC** has a **“moderate”** chloride ion penetration.
- **LC³** has mostly **"very low”** chloride ion penetration.
- Chloride Ion Penetration is up to 5x lower in LC³ than in OPC concrete.
- Due to very lo apparent diffusion coefficient

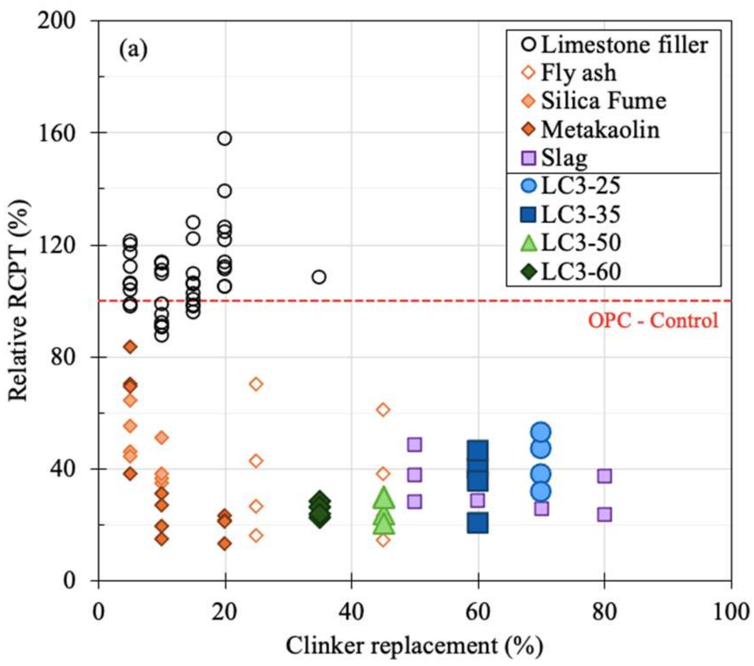




Relative RCPT - LC³ vs other SCMs

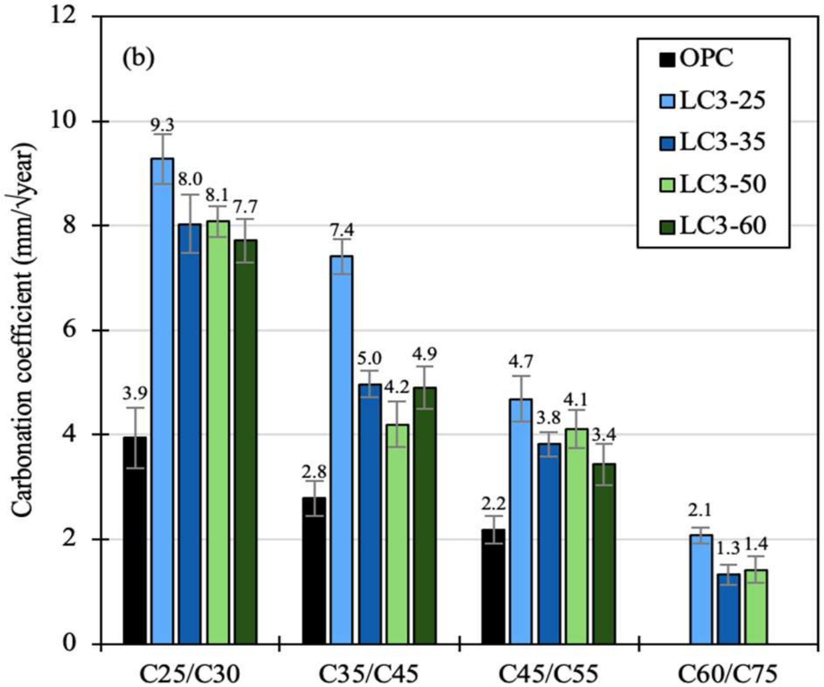
RCPT normalised to OPC

- Limestone filler – similar to or lower than OPC
- Fly ash, slag and LC³ – best
- LC³ has -20% to -53% RCPT than OPC
- LC³ and slag – lowest RCPT highest clinker replacement



Natural Carbonation

- LC^3 has 1.5 to 2.6 lower carbonation resistance than OPC.
- For higher strength classes, the carbonation depth decreases. LC^3 concrete C60/75 has carbonation closer to OPC.



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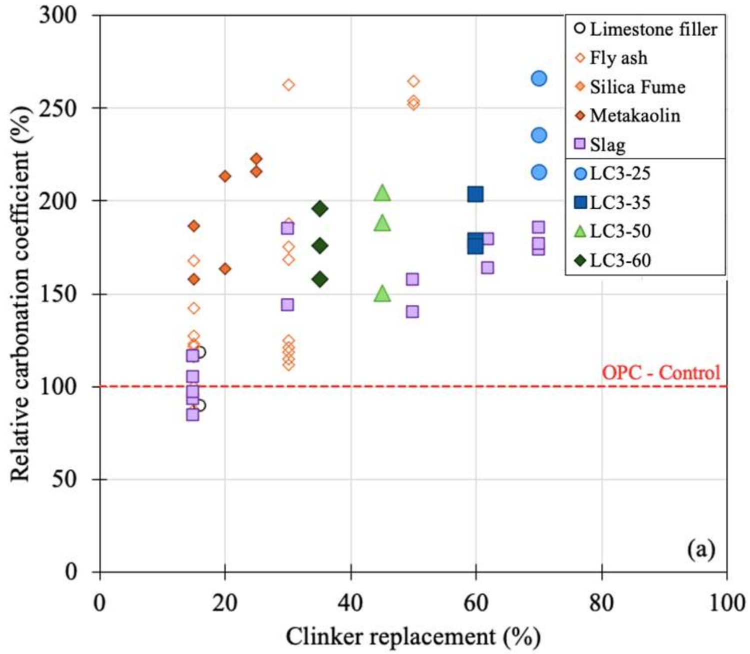
Relative Natural Carbonation - LC^3 vs other SCMs

Carbonation coefficient normalised to OPC

- Except for a 15% replacement of slag and limestone filler, blended cement (including LC^3) display higher carbonation than OPC.
- LC^3 has similar carbonation values to pozzolans but with a higher clinker replacement.
- For higher compressive strengths, the carbonation of LC^3 blends gets closer to the OPC and comparable to slag.



Limestone Calcined Clay Cement (LC^3)

- What is LC^3?
- Advantages
- Properties
- **History**
- **Applications**
- More

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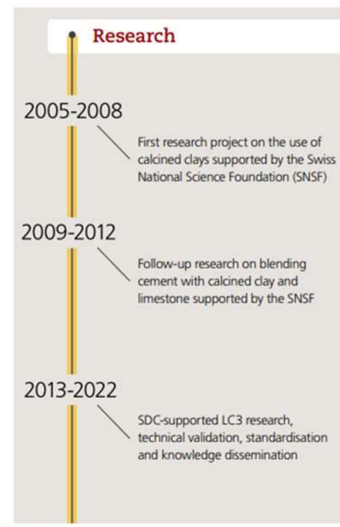
LC³ – The road to market success

2004 – UP TO DATE

RESEARCH

Everything started back in 2004..
Prof Karen Scrivener from EPFL in Switzerland and Prof Fernando Martirena from UCLV in Cuba discussed for the first time about the use of calcined clays for pozzolans.



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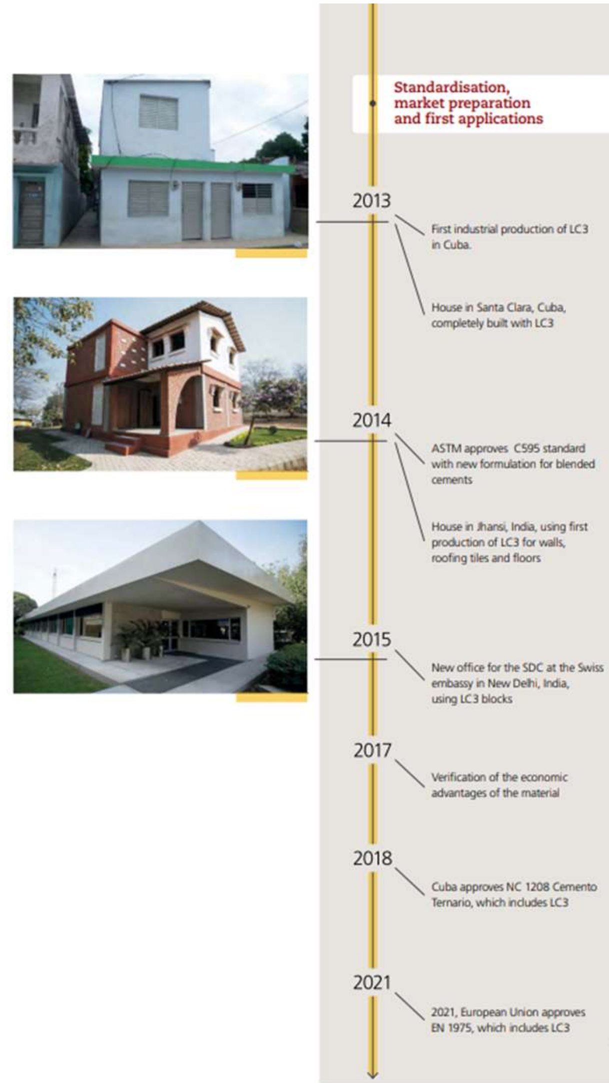
LC^3 – The road to market success

2013 – 2021

STANDARDISATION,
MARKET PREPARATION AND
FIRST APPLICATIONS



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LC³ – The road to market success

2019 – FUTURE

PRIVATE SECTOR UPTAKE
SCALING-UP

LC^3 – Recognised during COP28

COP28 “Energy Transition Changemaker” Award winner

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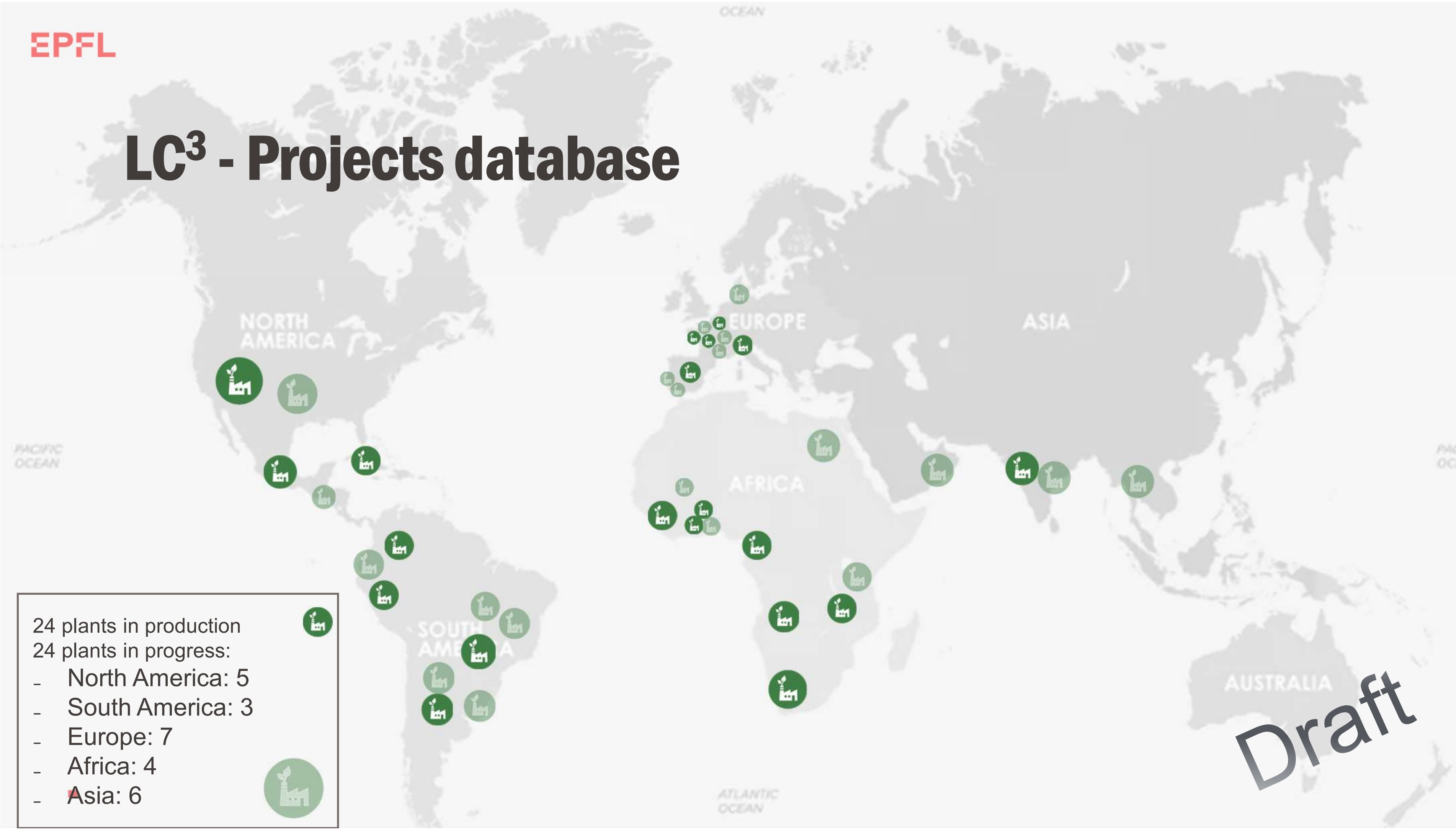
LC³ - Projects database



24 plants in production
24 plants in progress:
- North America: 5
- South America: 3
- Europe: 7
- Africa: 4
- Asia: 6

LC^3 - Applications

Demo house, India

Masonry building, Cuba

Swiss embassy, India

House Cape Town

© Kaolin Group, 2023

On site casting

Blocks, bricks, tiles

LC^3 application: tunnel and building in Columbia

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LC^3 application: highway viaduct in Columbia

LC³ – Application: Tilia Tower Lausanne

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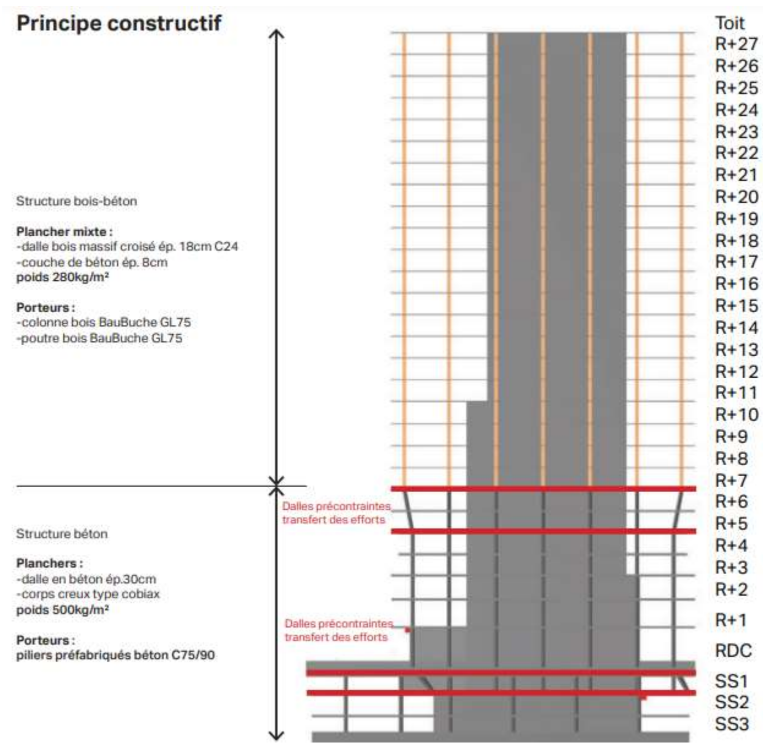
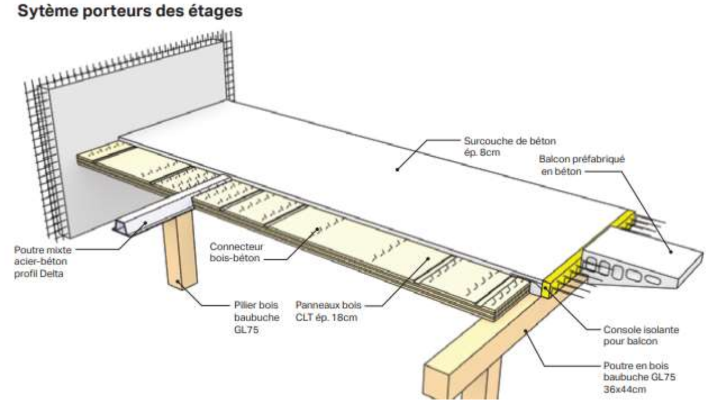
Tilia Tower



<u>The building:</u>

27 floors: -3 to +7 in concrete, + 8 to +27 in wood/concrete
Facade made of concrete panels
LC3 is used for slabs (30cm thickness) and walls

Sytème porteurs des étages



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LC³ – Application: Rolex campus

New Rolex factory in Bulle, Switzerland – expected completion in 2029.

Multi-building complex (project currently under public consultation)

380 m in length,
10'000 m² area
98% of its heating will be derived from renewable energy sources.

This project exemplifies sustainability in the construction industry, addressing both embodied carbon (CO_2 emissions from the construction process) **and operational carbon** (CO_2 emissions from building operations).

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Limestone Calcined Clay Cement (LC^3)

- What is LC^3?
- Advantages
- Properties
- History
- Applications
- **More**

To expand your knowledge about LC3

To read more about History, Media, Recognitions, Publications

Visit our website:

👉 https://lc3.ch/

To see the recent achievements and stay updated about LC3

@LC3Cement

@LC3Cement

LC3-Low Carbon Cement

LC3-Low Carbon Cement

LC3-Limestone Calcined Clay Cement

To join our research on LC3

Apply for one of the semester projects at LMC!

Overview on the last Lecture day pf the course.

7 PhDs projects

2 Post in charge

Semester Projects

Addressing the workability challenge of low-carbon blended cements: developing a new standard test method for mixing and workability.

E T

Lab: LMC

Sections: SMX

Supervisor: Dr. Beatrice Malchiodi

[read on]

Learning objectives

Now, at the end of this class, you are able to…

- Contextualise the importance of implementing blended cement.
- Define and identify different blended cements.
- Understand how to measure the reactivity of SCMs and evaluate their performance.
- Define the advantages of using LC3 amongst the other available SCMs
- Define the properties and best applications for LC3
- See the historical evolution of LC3 and its real and potential impact

Always design in a durable and sustainable way!

Course Schedule

Wk #	Class date	Title	Lecturer
1	11/09/2024	Introduction/literature review	Prof. Karen Scrivener /Dr. Alastair Marsh
2	18/09/2024	Durability of cementitious materials	Dr. Beatrice Malchiodi
3	25/09/2024	Cement hydration	Prof. Karen Scrivener
4	02/10/2024	Characterisation techniques for cementiitous materials	Dr. Federica Boscaro
5	09/10/2024	Presentation 1	
6	16/10/2024	Admixtures	Dr. Federica Boscaro
7	30/10/2024	Presentation 2	
8	06/11/2024	LCA - Life Cycle Analysis	Dr. Alastair Marsh
9	13/11/2024	Sustainability approaches for construction	Dr. Alastair Marsh
10	20/11/2024	LC3 - Limestone Calcined Clay Cement	Dr. Beatrice Malchiodi
11	27/11/2024	Concrete design	Dr. Beatrice Malchiodi
12	04/12/2024	Concrete saving through a better structural design / Q&A on Presentation 3	Porf. David Ruggiero
13	11/12/2024	Presentation 3	
14	18/12/2024	08:15-09:00 Precast concrete, Sustainability in Concrete and Building Codes	Prof. David Fernandez-Ordoñez
		09:10-09:50 Circularity: Reuse of concrete elements	Prof. Corentin Fivet
		09:50-10:00 Semester projects at LMC	

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LABORATORY OF CONSTRUCTION MATERIALS

Questions?

Advanced cementitious materials, MSE 420

Lecture 10: SCMs and Limestone Calcined Clay Cement (LC3)

Dr. Beatrice Malchiodi
beatrice.malchiodi@epfl.ch
20 November 2024