LC^3: reducing CO2 emissions of cementitious materials fast and at scale

LC^3:一个可以快速和大规模减少二氧化碳排放的水泥基材料方案

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瑞士洛桑联邦理工学院Karen Scrivener教授

Main messages || 主要信息

- There is no magic bullet

  没有万能的解决办法

- We can do a lot applying multiple solutions, mostly already known

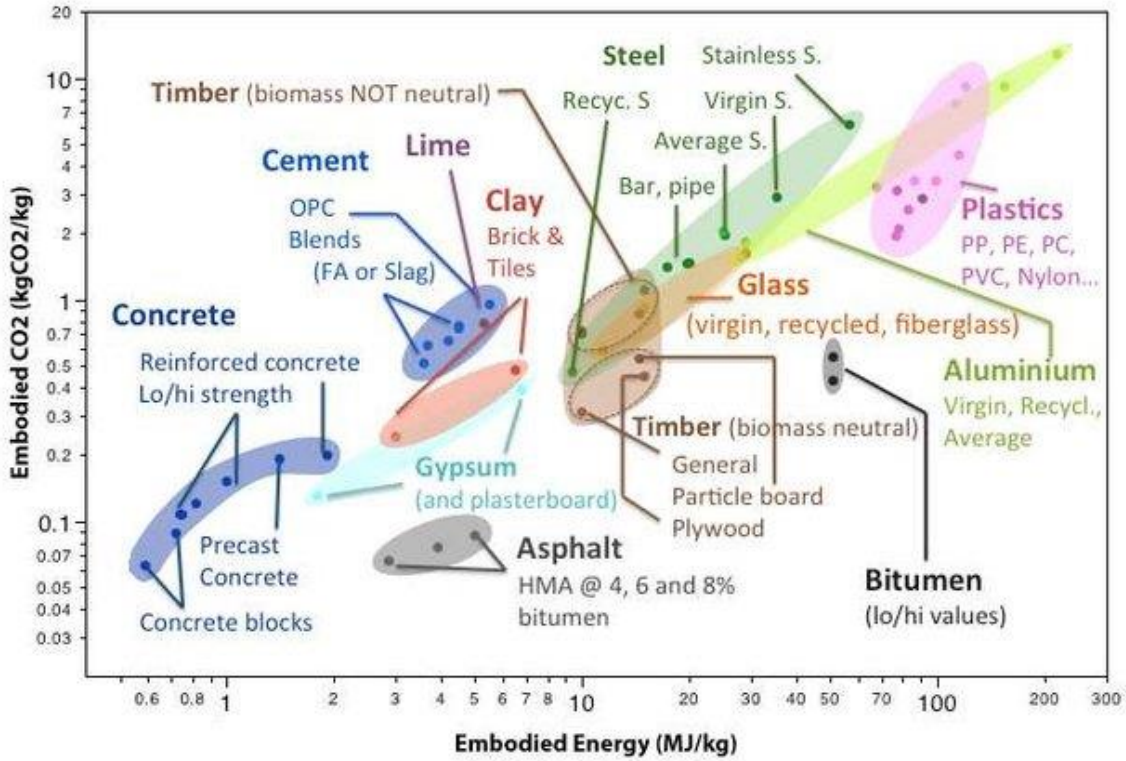
  在已知范围内，我们可以做很多事情，应用多种解决方案

Cementitious Materials: Concrete, Mortar || 水泥材料：混凝土、砂浆

Cementitious materials make up >50% of everything we produce
水泥基材料占所有生产产品的50%以上

It is only for this reason they account for 8% of CO_2 annually.
仅出于这个原因，它每年造成8%的碳排放

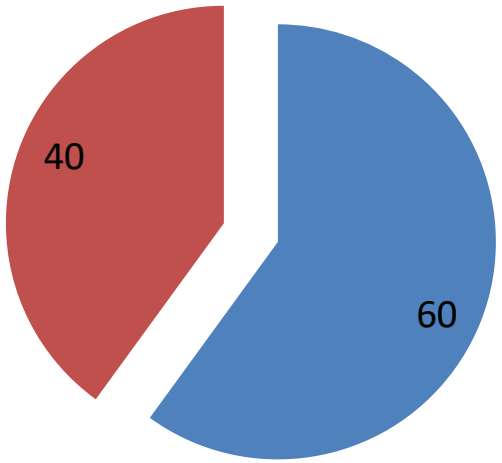
Low intrinsic environmental impact
但本质上对环境影响较小



To replace 25% of cementitious with timber would require planting a forest 1,5 x the size of India
如果想用木材取代25%的水泥，需要再种植印度国土面积1.5倍的森林

Origins of CO_2 emissions in clinker production:
熟料生产中二氧化碳排放的来源：

CO_2 from the clinker remains around 75% through to the Concrete
熟料中的二氧化碳在混凝土中仍占75%左右



1 tonne of clinker leads to the emission of 750 – 900 kg CO_2
Average 850kg/t
1吨熟料可排放750 – 900公斤CO_2
平均850公斤/吨

- CaCO3 $CaCO_3$ 分解（化学） decomposition (CHEMICAL)
- Fuel 燃料

$$CaCO_3 \rightarrow CaO + CO_2$$

Limestone 80% of raw material

石灰石 80% 原料

The production process is highly optimised up to around 80% of thermodynamic limit.
生产过程经过高度优化，最高可达热力学极限的80%左右。
It is estimated that **< 2%** further savings can be made here
据估计，这里可以节省< 2%
Use of waste fuels, which can be **> 80%** reduces the demand for fossil fuels
使用废燃料，可减少超过80%对化石燃料的需求

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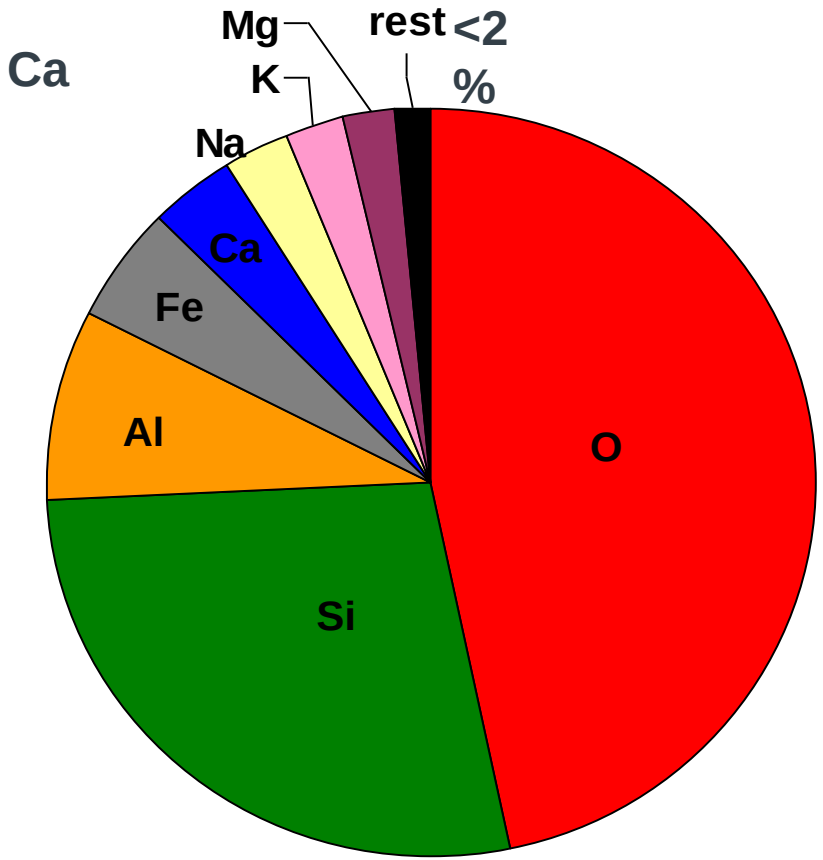
Can we make cement with a different chemistry?

我们可以用不同的化学成分制造水泥吗?

What is available on earth? 土壤中有什么可用的?



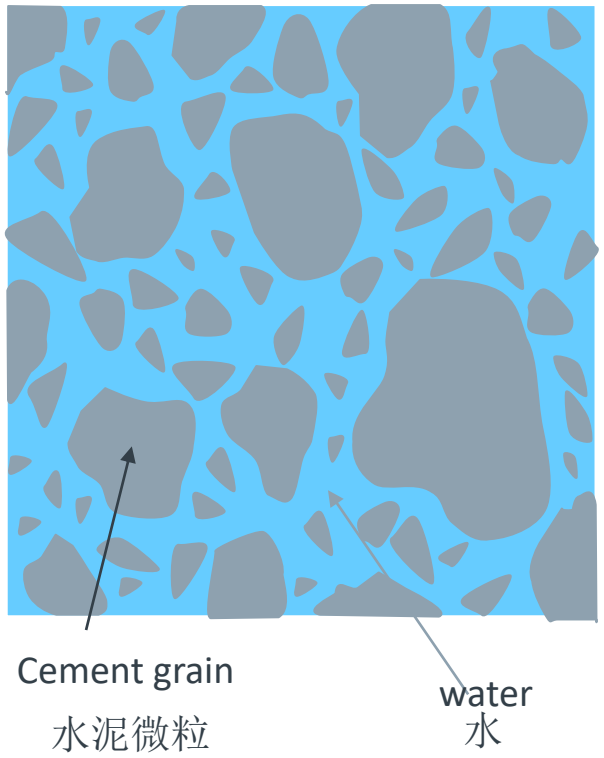
8 elements make up more than 98% of the earth's crust

8种元素占地壳的98%以上

How does cement work?

水泥是如何工作的?

How cement works: ||水泥是如何工作的：



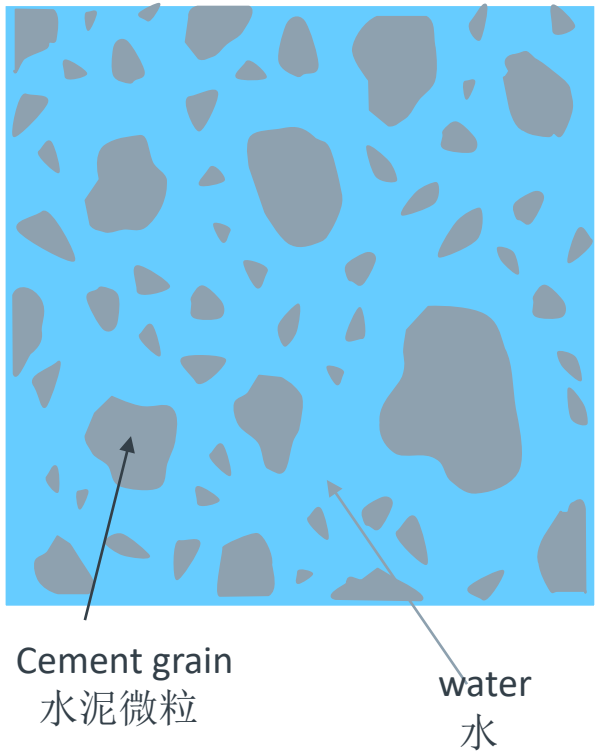
We mix the grey cement powder with water.

我们将灰水泥粉与水混合

To start with the grains are just floating about in the water and we can cast the concrete into moulds

首先，颗粒只是漂浮在水中，我们可以将混凝土浇铸进模具

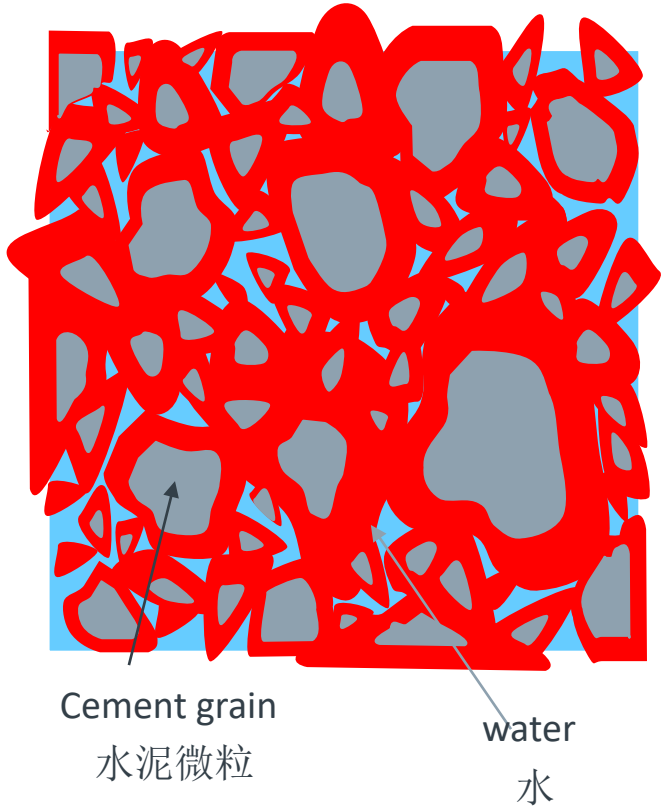
How cement works: ||水泥是如何工作的：



The cement grains dissolve in the water

水泥颗粒溶于水

How cement works: ||水泥是如何工作的：



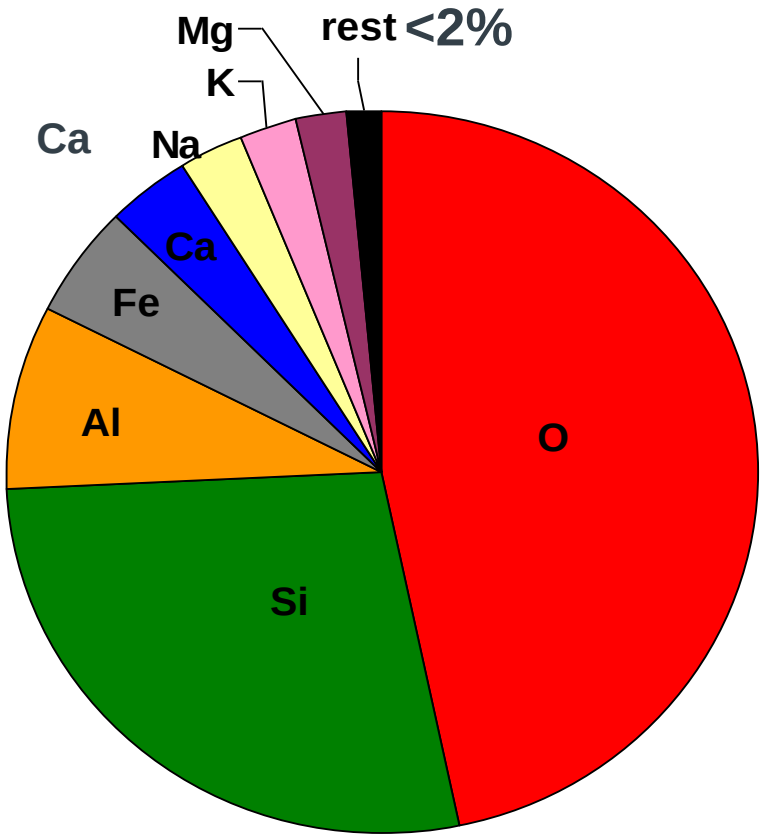
The cement grains dissolve in the water

水泥颗粒溶于水

And then precipitate *Hydrates* – new solids which have higher volume and hold the grains together: creating a rigid solid

然后沉淀水合物 – 具有更高体积并将颗粒聚合在一起形成新固体：
刚性固体

What is available on earth? 泥土中有什么可用的?



Na_2O
K_2O

Too soluble 极易溶解

Fe_2O_3
MgO

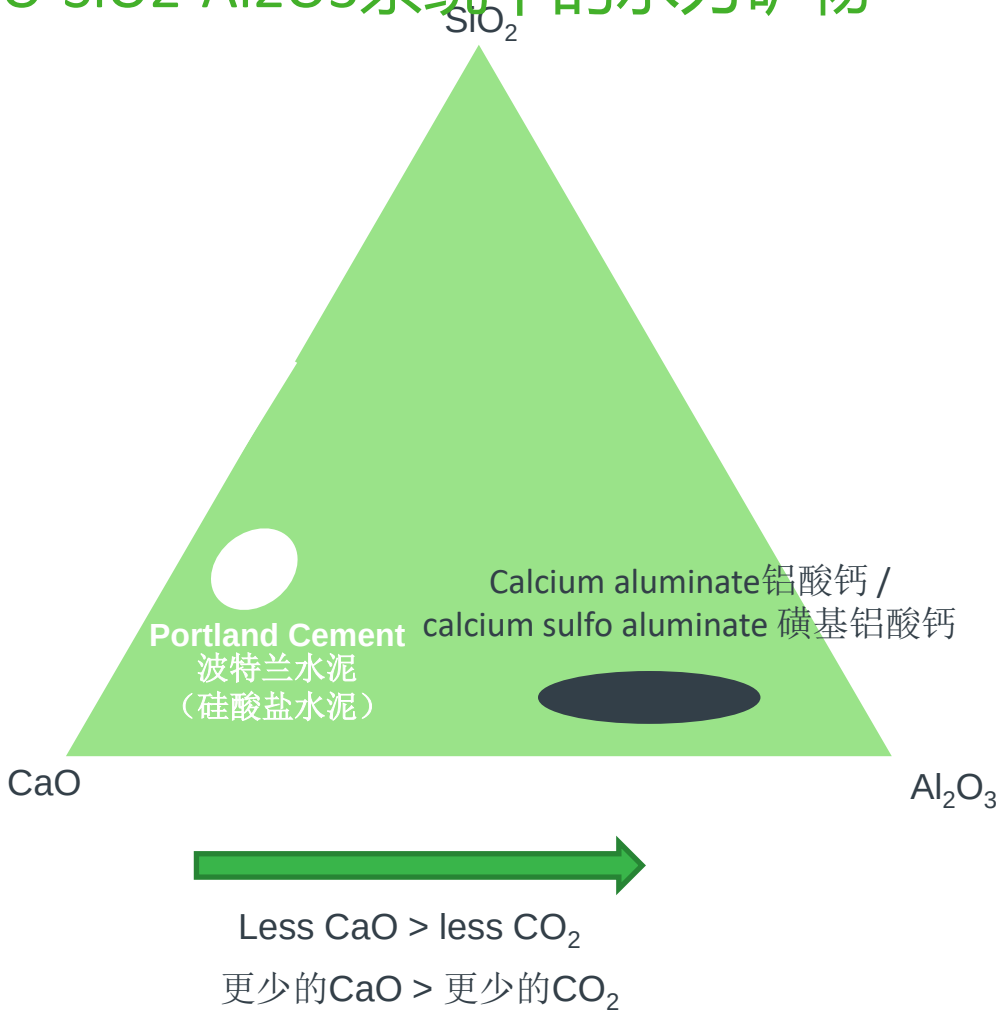
Too insoluble in alkaline solutions 不易溶于碱性溶液

CaO
SiO_2
Al_2O_3

The most useful 最有用

Hydraulic minerals in system $CaO-SiO_2-Al_2O_3$

CaO-SiO2-Al2O3系统中的水力矿物



BUT, what sources of minerals are there which contain Al_2O_3 >> SiO_2 ?
但是，含有Al_2O_3>>SiO_2的矿物质来源是什么?

Bauxite – localised, under increasing demand for Aluminium production, EXPENSIVE
铝土矿 – 本地化，铝生产需求不断增加，**价格昂贵**

Even if all current bauxite production diverted would still only replace 10-15% of current demand.
即使目前所有铝土矿生产都转移，仍然只能取代当前需求的10-15%。

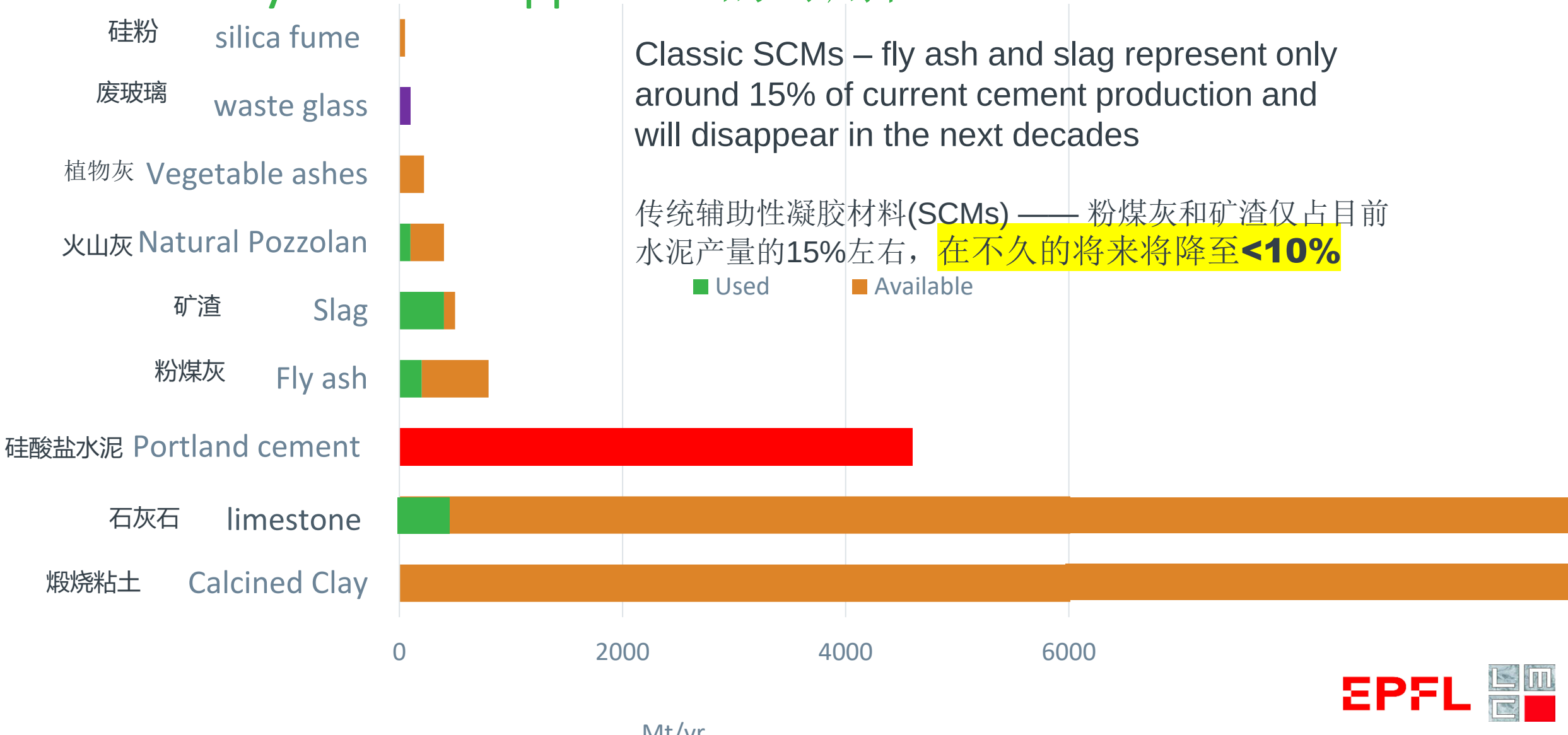
Even after nearly 50 years CSA production in China is <0.1% of OPC
and falling
即使经过近50年，中国的CSA产量仍<OPC的0.1%，并且正在下降

Portland based cements are an inevitable consequence of the chemistry and geology of the earth
波特兰水泥（硅酸盐水泥）是化学和地质学的必然结果

Blended cements are the most realistic options to reduce CO_2 and extend resources

混合水泥是减少二氧化碳和扩大资源最现实的选择

Availability of SCMs || SCMs的可用性



Classic SCMs – fly ash and slag represent only around 15% of current cement production and will disappear in the next decades

传统辅助性凝胶材料(SCMs) —— 粉煤灰和矿渣仅占目前水泥产量的15%左右，在不久的将来将降至**<10%**

There is no magic solution 没有万能的解决方案

- Blended with SCMs will be best solution
  for sustainable cements for the foreseeable future
  在可预见的未来，与SCMs的拌合将是可持续水泥的最佳解决方案

- **The only material available in viable quantities is calcined clay**.
  唯一真正有潜力大量供应的材料是煅烧粘土

- **Synergetic reaction** of calcined clay and limestone
  allows high levels of substitution
  煅烧粘土和石灰石的协同反应允许大范围的取代

EPFL led LC^3 project supported by SDC. **Started in 2013**
洛桑联邦理工学院领导的LC3项目始于2013年。

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

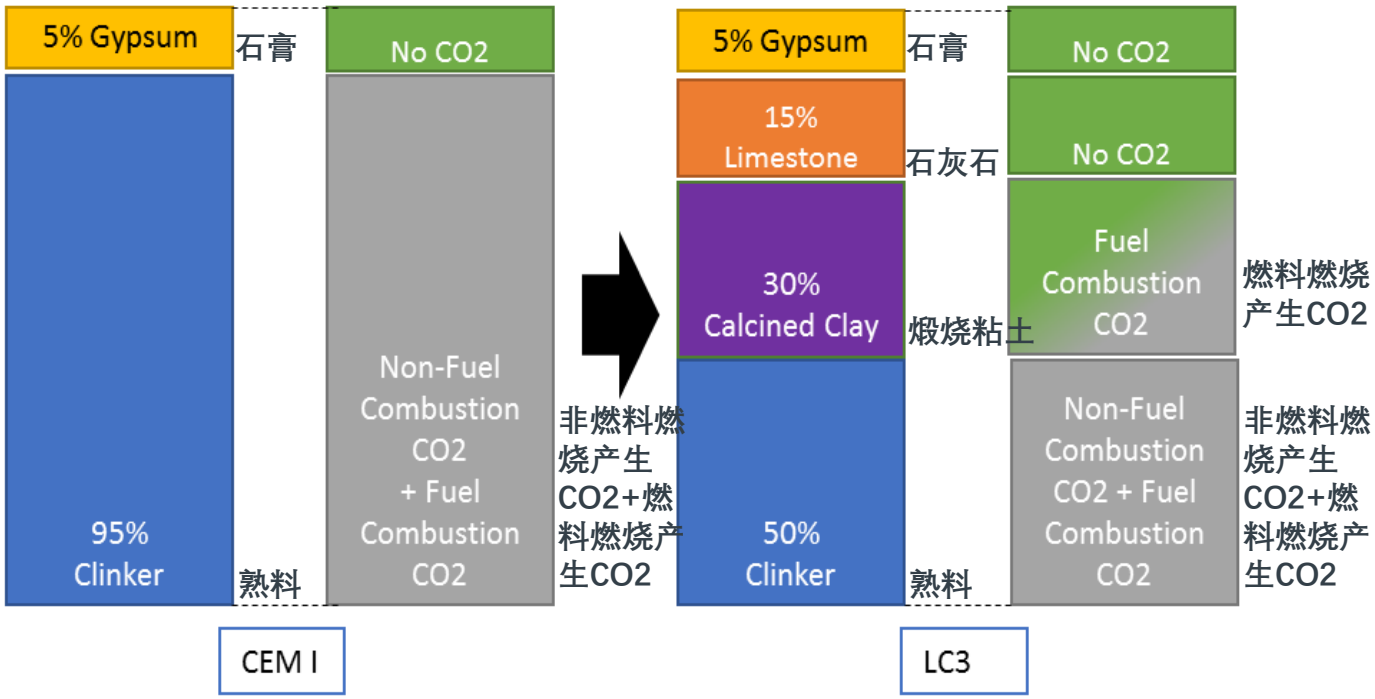
Limestone Calcined Clay Cement LC3

EPFL

Limestone Calcined Clay Cement LC3

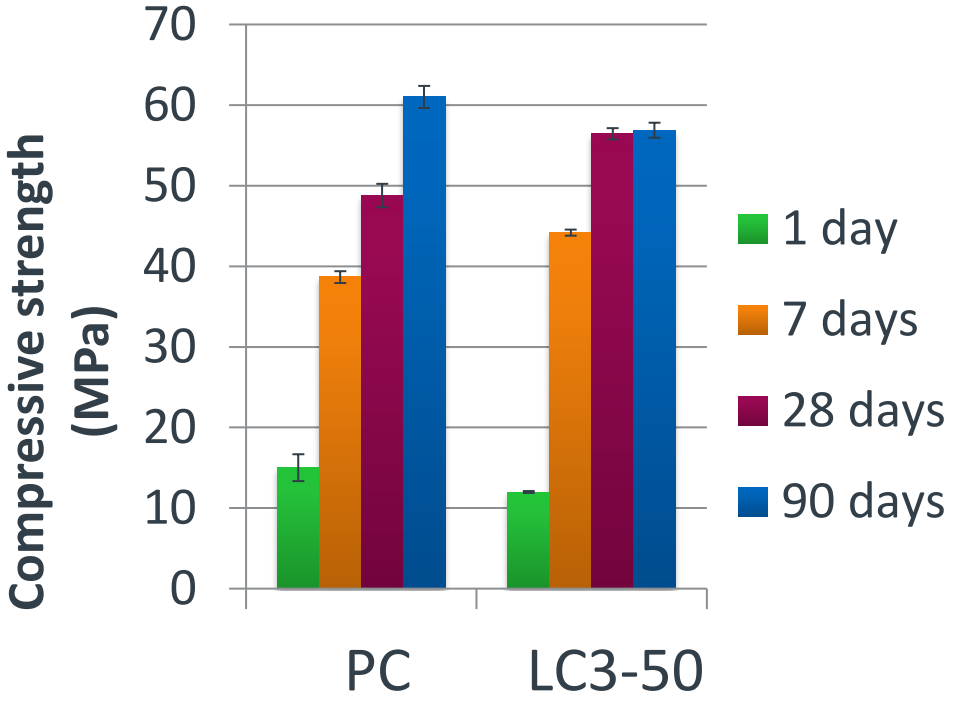
LOW CARBON LOW COST LOW CAPITAL

What is LC³ 什么是LC³？



LC³ is a family of cements, the figure refers to the **clinker** content

LC³是水泥家族的成员，图片中表明熟料的成分



- 50% less clinker 减少50%熟料
- 40% less CO_2 减少40%CO_2排放
- Similar strength 相同强度
- Better chloride resistance 抗氯性更好
- Resistant to alkali silica reaction 抑制碱与硅石的反应

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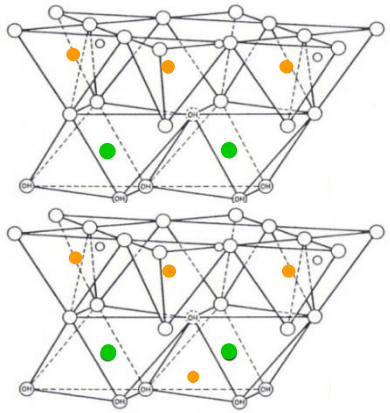
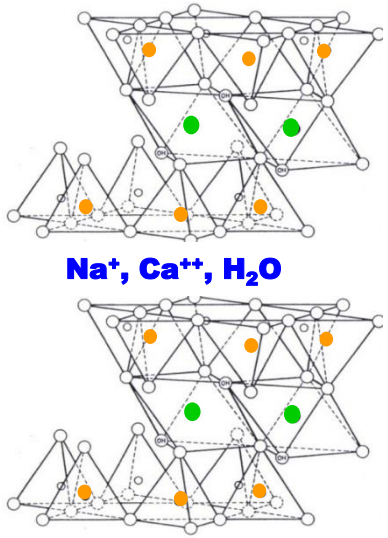
What kinds of clay are suitable?
哪种粘土适合呢？

Three basic clay structures 三种基本的粘土结构

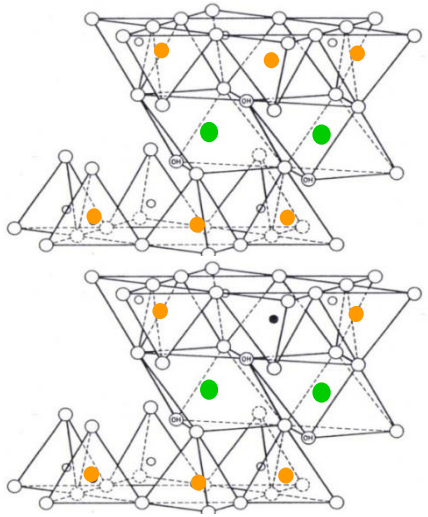
Kaolinite (1:1) 高岭土



Montmorillonite (2:1)
(Smectites) 蒙脱石



Illite (Micas) (2:1)
伊利石（云母）

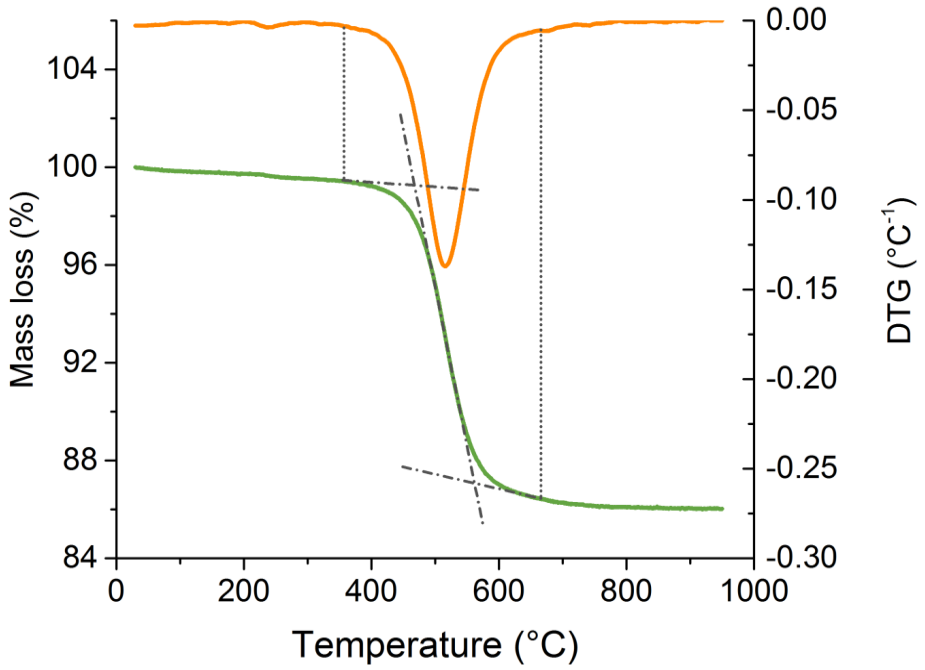


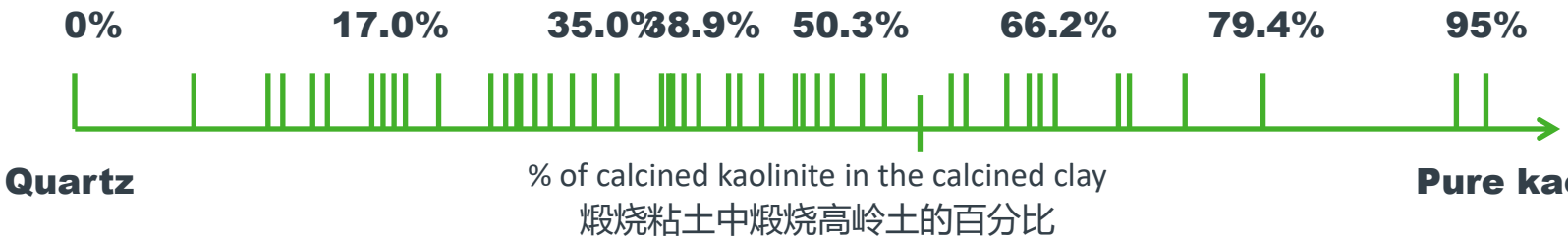
"Metakaolin", sold as high purity product for paper, ceramic, refractory industries
Requirements for purity, colour, etc, means expensive cement (3-4x price)
偏高岭土作为高纯度产品出售，用于制造纸、陶瓷、耐火材料工业，对纯度、颜色等均有要求。一般是水泥价格的3至4倍

Clays containing metakaolin available as wastes 低偏高岭土含量的粘土很多被当作废料
– over or under burden NOT agricultural soil 非农业土壤
Much less expensive and often available close to cement plants 价格便宜得多，且离水泥厂近

Over 70 clays studied from around the world
研究来自世界各地的70多种粘土

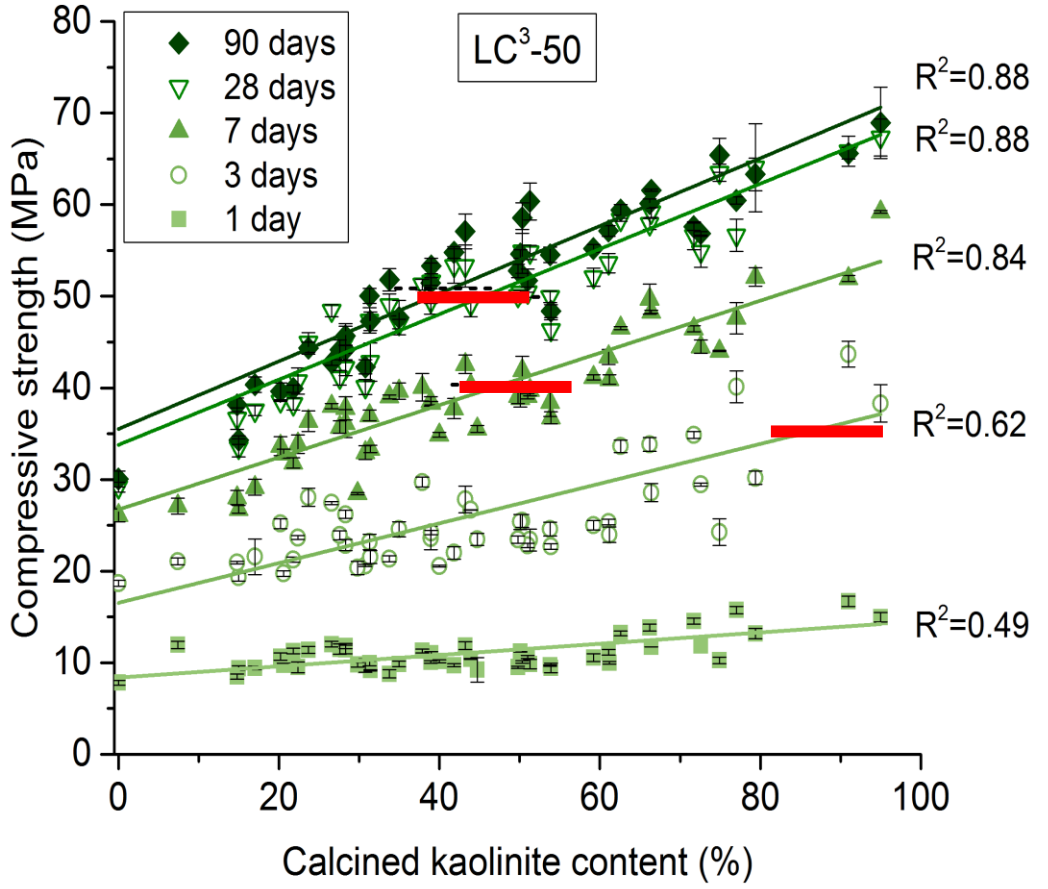
- Different calcination conditions
  不同的煅烧条件
- Different compositions, impurities
  不同的成分，杂质
- Different physical properties
  不同的物理性质





Benchmark test of clay strength
粘土强度基准测试

- Compressive strength EN 196-1 at 1, 3, 7, 28, 90 d
  基于标准EN 196-1分别在1，3，7，28，90天的抗压强度
- Linear increase of strength with the MK content of calcined clays
  强度随煅烧粘土的MK含量线性增加
- Similar strength to PC for blends containing 40% of calcined kaolinite from 7d onwards
  第7天开始，含有40%煅烧高岭土的混合物的强度与PC相似
- At 28 and 90 days, little additional benefit >60%
  在 28 天和 90 天时，少量额外的好处 >60%
- Minor impacts of fineness, specific surface and secondary phases
  细度、表面和二次相的轻微影响



Calcined kaolinite content overwhelming parameter

煅烧高岭土成分具有压倒性优势

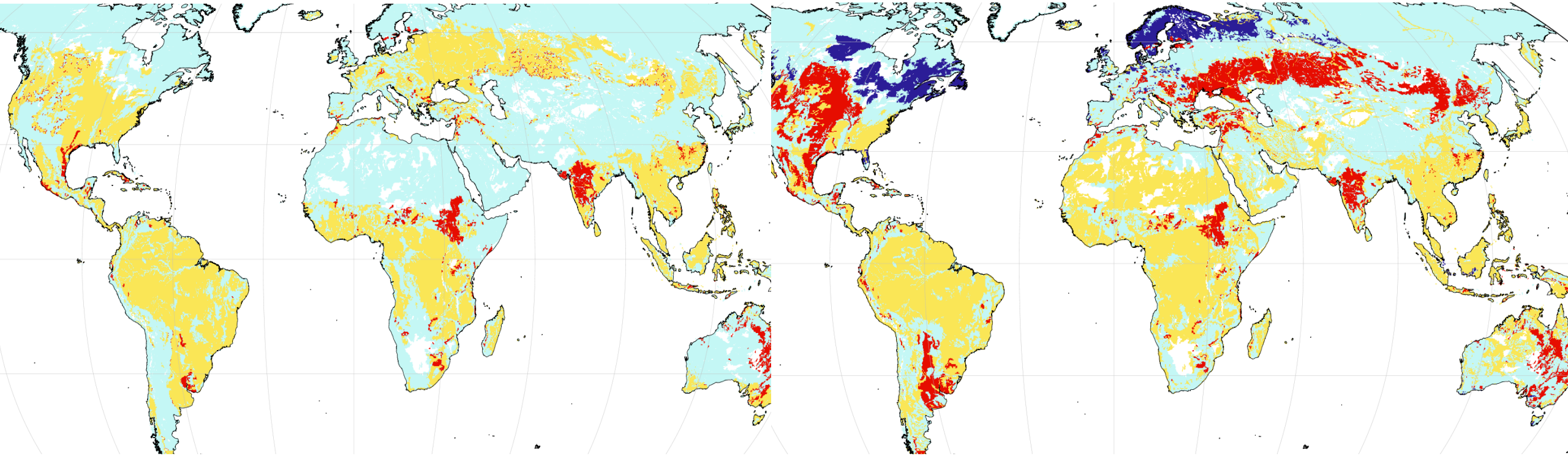
Ideal kaolinite content 30-60% 理想的高岭土含量为30-60%

- Higher contents, possible to use more limestone 含量越高，可能会使用更多的石灰石
- *Even better return on investment and climate-friendly* 甚至有更好的经济学和生态学效应
- Lower contents can be enriched by separation 较低的含量可以通过分离达到富集的目的
- *Separated, fine quartz can be sold as a separate product* 分离出来的精细石英可以作为单独的产品出售
- These kind of materials are not documented in official reserves of “kaolin”
  这些材料在 "高岭土 "的官方储备中没有记录
- The amounts of suitable materials 100s of times higher than such reserves
  实际上合适粘土材料的总量比这种储备高100多倍

Distribution of Kaolinitic clays 高岭土粘土的分布

Ito and Wagai, Scientific data 2017

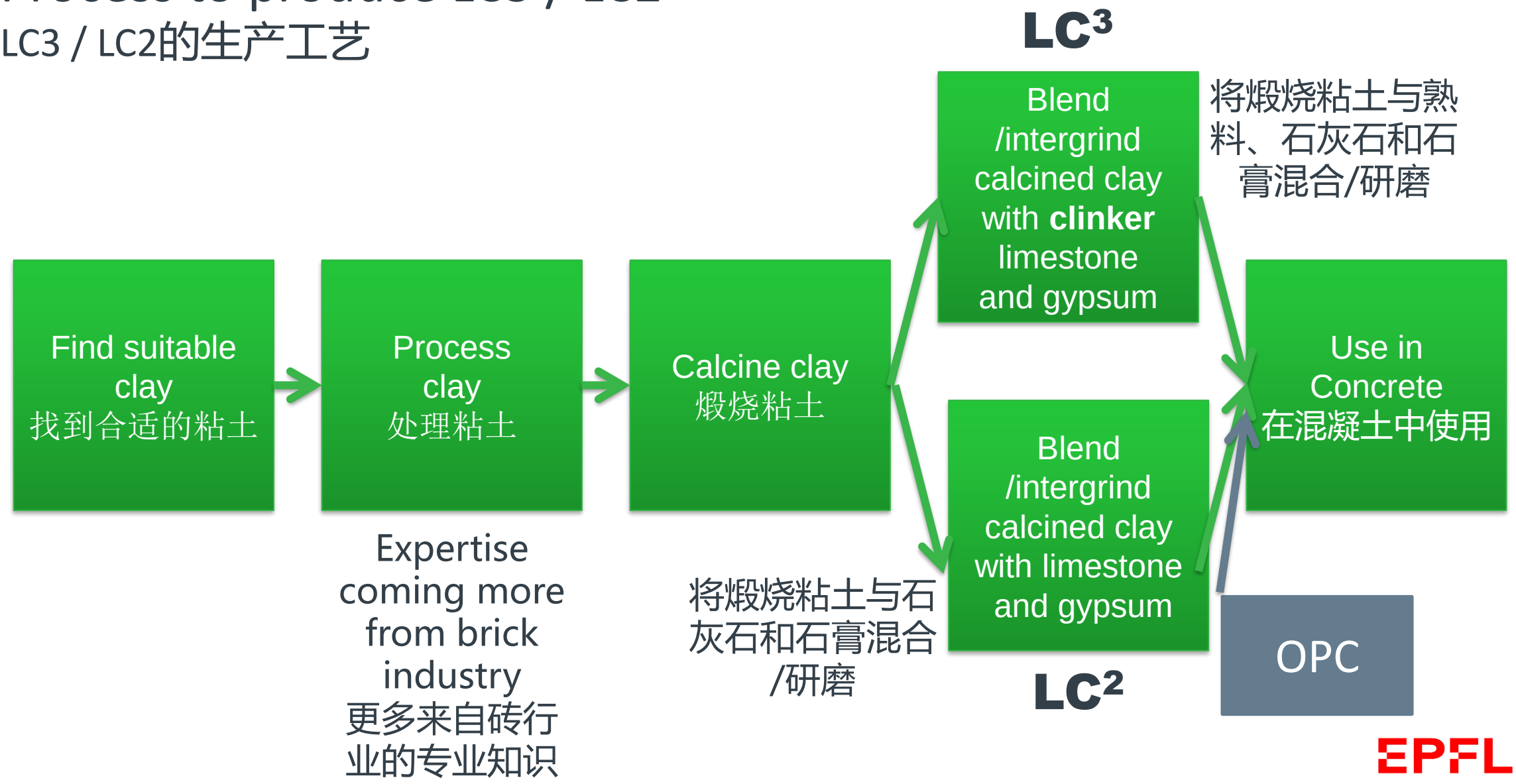
0-5m >5m



Ilite/mica Kaolinite Smectite Vermiculite

Process to produce LC3 / LC2

LC3 / LC2的生产工艺



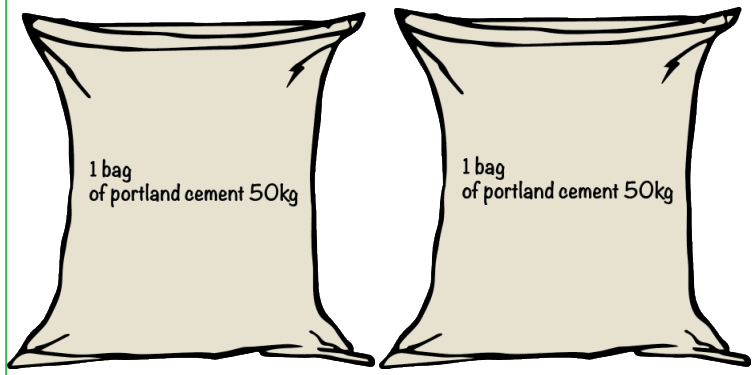
Limestone Calcined Clay Cement LC3

LOW CARBON LOW COST LOW CAPITAL

LC3
Blend at cement plant
在水泥工厂混合

Ordinary Portland Cement 100kg = 2 bags
Conventional solution

普通波特兰水泥：100kg=2袋
传统方法

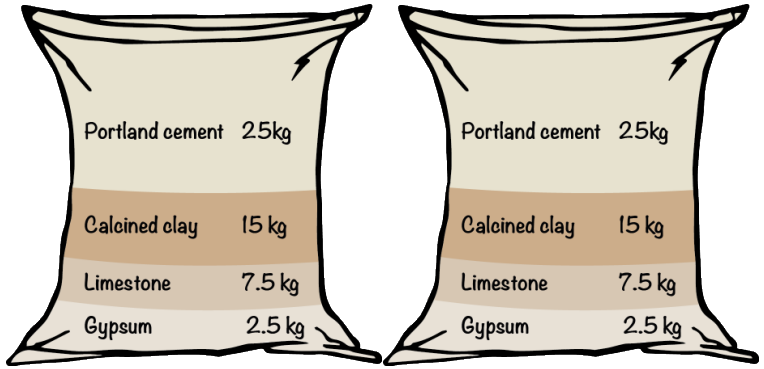


CO2 emissions = 80kg per 100kg

每**100kg**普通水泥排放**80kg**二氧化碳

LC3: 100kg = 2 bags
(pre-mixed at factory) Needs new standards in most countries
Clinker factor = 50%

LC3：100kg=2袋
（工厂预混）在大多数国家需要新的标准；熟料含量50%



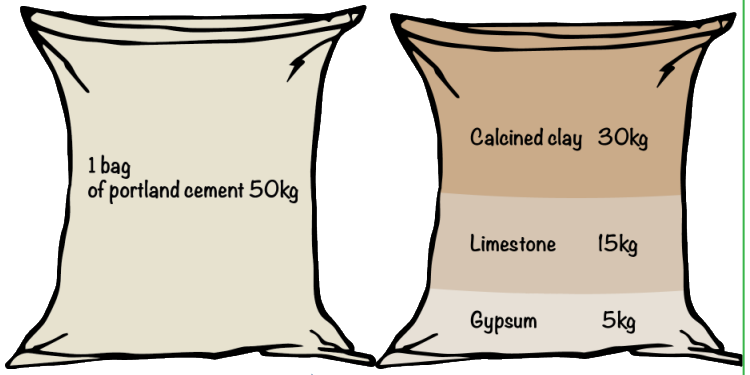
每**100kgLC3**水泥排放**50kg**二氧化碳

CO2 emissions = 50kg per 100kg

LC2
Blend at ready mix plant
在预拌机混合

LC2: 100kg = 1 bag Portland + 1 bag LC2
(mixed at concrete ready mix site) Already possible with existing standards in most countries, Clinker Factor also 50%

LC2：100kg=1袋波特兰水泥+1袋LC2
（在施工现场混合）在大多数已有标准的国家可以实现；熟料含量50%



每**100kgLC2**水泥排放**50kg**二氧化碳

CO2 emissions = 50kg per 100kg

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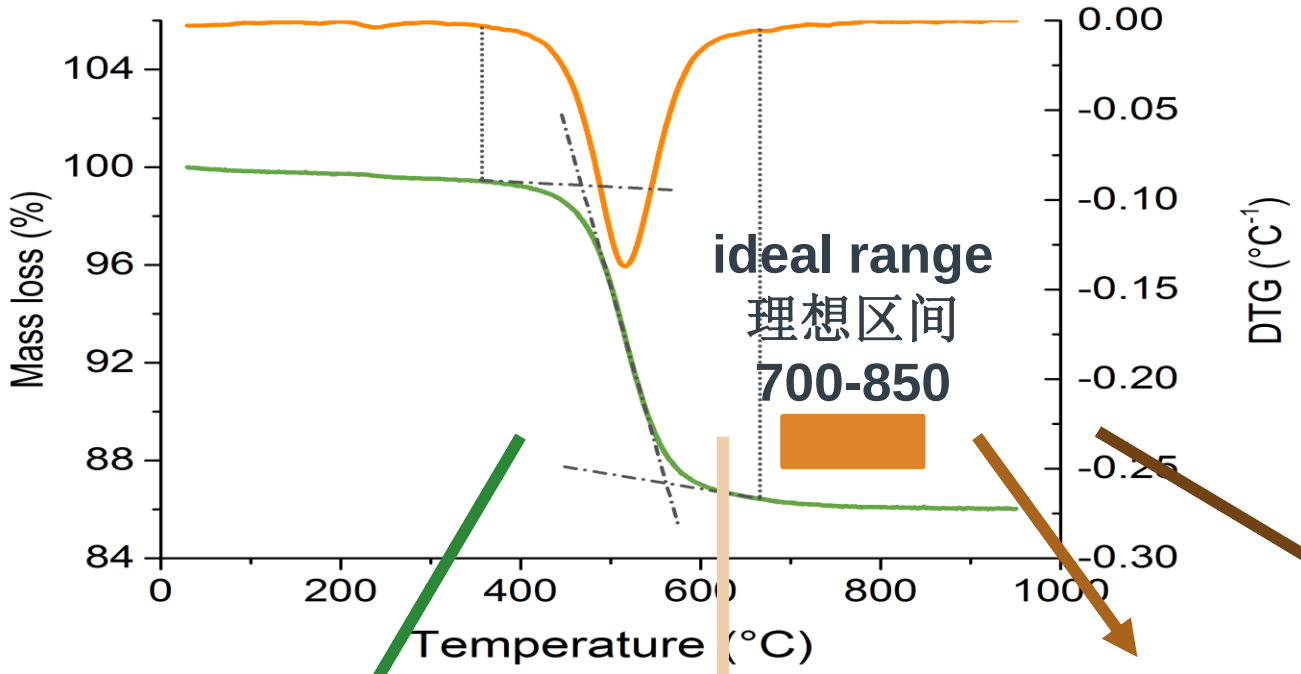
Calcination of clay
粘土的煅烧

Temperature window 700-850°C || 温度窗口 700-850°C



<600 °C
Not reactive
不发生反应

600-700 °C
dehydroxlation complete but reactivity increases
脱氢氧化完成
反应性增加

850-1000 °C
Surface area reduced reactivity decreases
表面积减少
反应性降低

>1000 °C
crystalline phases formed no reactivity
晶相形成
无反应性

Calcination methods: || 煅烧方法：

Rotary kiln 回转窑

- Advantages 优势
  - Robust 结实耐用
  - Tolerant to moisture content up to 20%耐湿含量高达20%
  - Fairly large particles (few mm) can be calcined efficiently 可以有效地煅烧相当大的颗粒（几毫米）
  - Easy colour control technology容易控制颜色
- Disadvantages 劣势
  - Reputed to have higher energy consumption 能耗更高

Flash calcination 快速煅烧

- Advantages 优势
  - Calcination more energy efficient 能效更高
  - Lower opex? 更低的运行成本
- Disadvantages 劣势
  - Very low moisture (<5%) 非常低的耐湿量(<5%)
    - Dryer and dry storage silo required需要干燥机和干燥储存仓
  - Small particles 小颗粒
    - crusher 需要使用破碎机

But real kiln built in Ivory Coast has energy of 550 kCal/ kg, 2.3 MJ/kg 但是在象牙海岸建造的真实窑炉的耗能为550 kCal/ kg, 2.3 MJ/kg

To date testing many clays indicates no significant difference in reactivity

迄今为止，对多种粘土的测试表明，反应性能没有显着差异

House built in Santa Clara, Cuba with LC3
在古巴圣克拉拉用LC3建造的房子

Demonstration structure 示范结构

Around 14 tonnes of CO_2 saved
Compared to existing solutions
与现有解决方案相比，减少约 14 吨CO_2排放

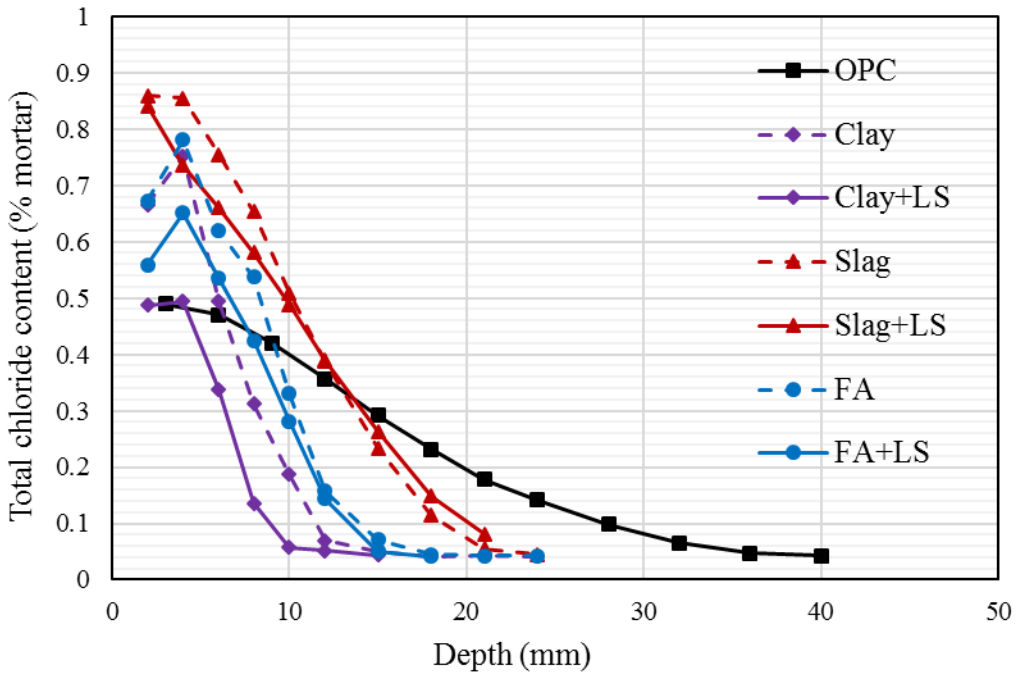
New Calcination plant Ivory Coast
象牙海岸新煅烧厂

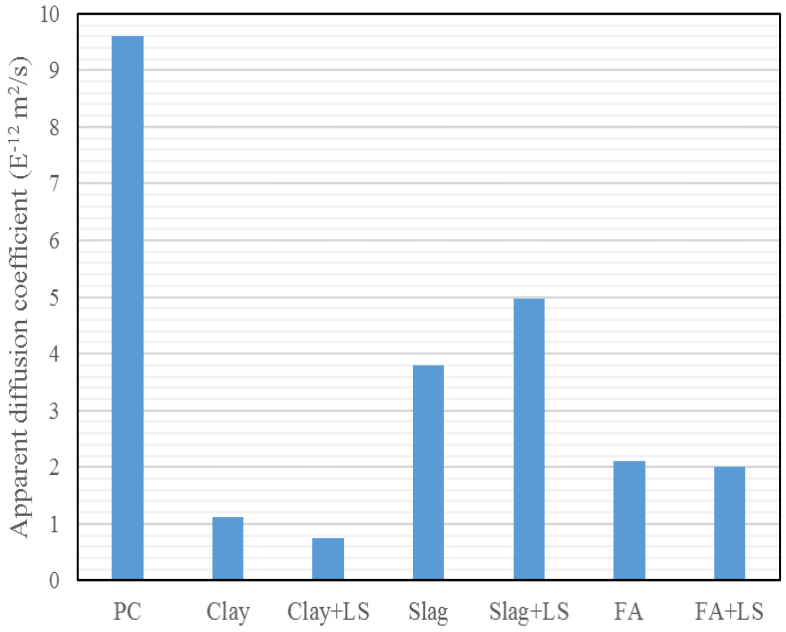
Colour control at Ivory Coast plant 象牙海岸工厂对颜色的控制

Key Advantages 关键优势

- Chloride resistance 耐氯性
- Suppression of alkali silica reaction
  抑制碱与硅石的反应

Chloride ponding ASTM 氯化物沉积 ASTM





Apparent diffusion coeffs.
明显的扩散系数

Workability 工作性能

- Workability, good properties can be controlled by admixtures

  可通过外加剂控制获得良好的工作性能

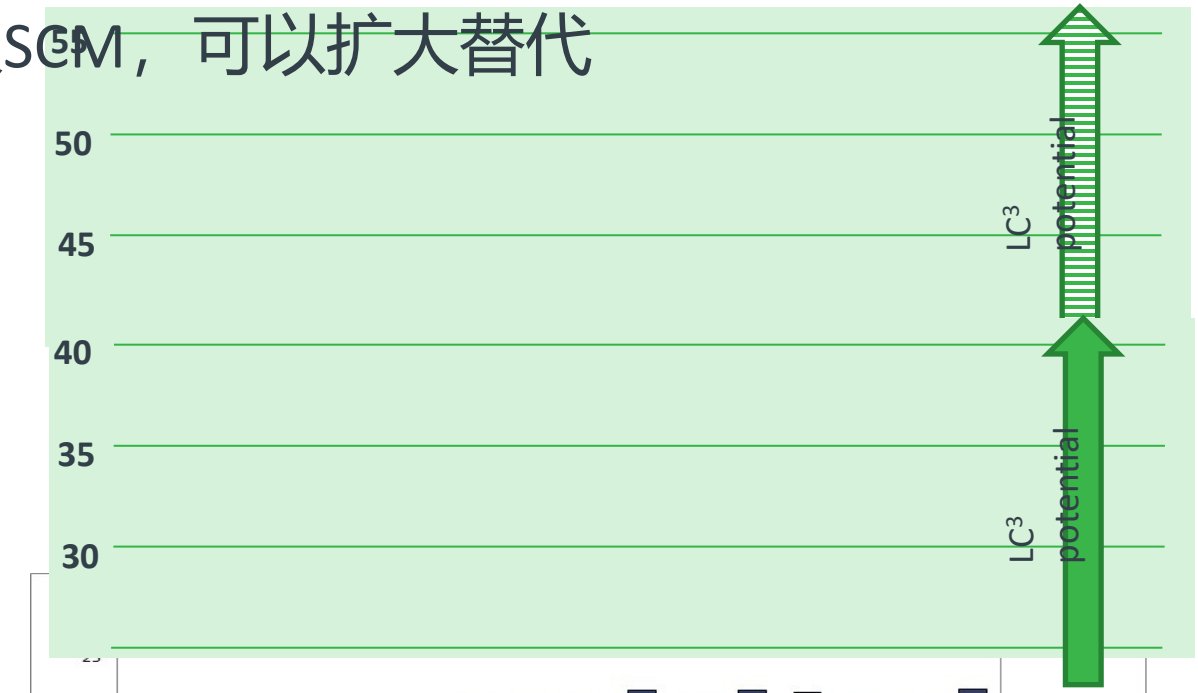
- New admixtures coming on the market

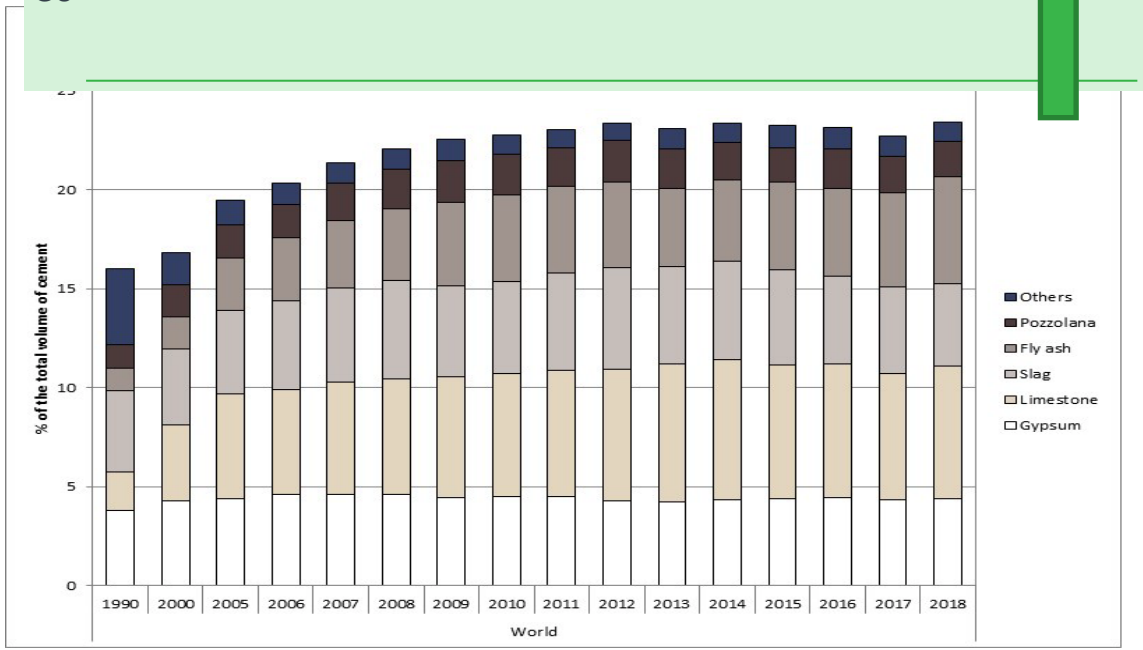
  新外加剂即将上市

- Good cohesion, well suited for SCC

  粘聚力好，很适合自密实混凝土

Calcined Clay only SCM which can expand substitution
煅烧粘土仅SCM，可以扩大替代





> 800 million Tonnes CO_2/yr

> 800 百万吨 CO_2/年

> 400 million Tonnes CO_2/yr

> 400 百万吨 CO_2/年

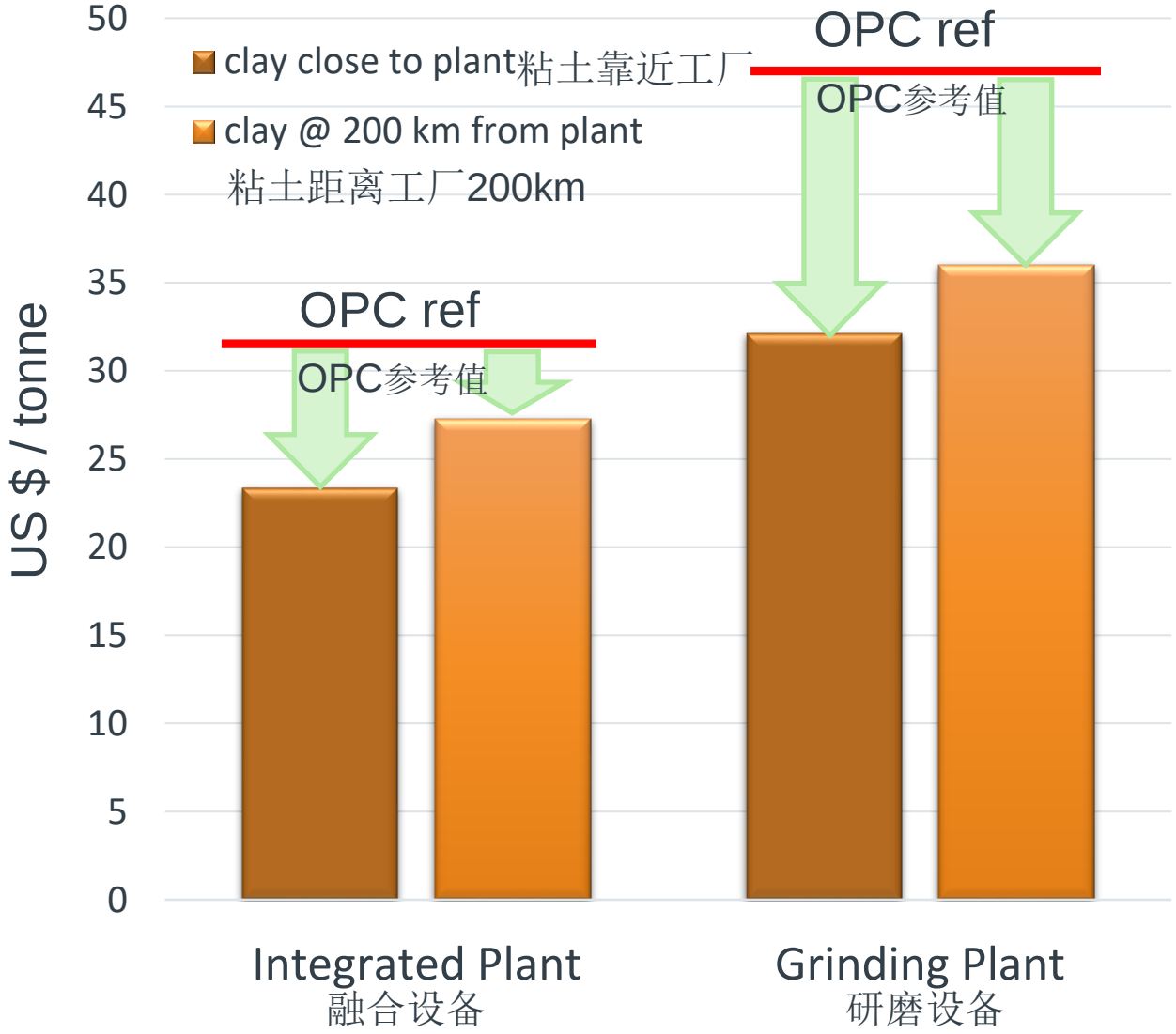
Financial Feasibility
财务可行性

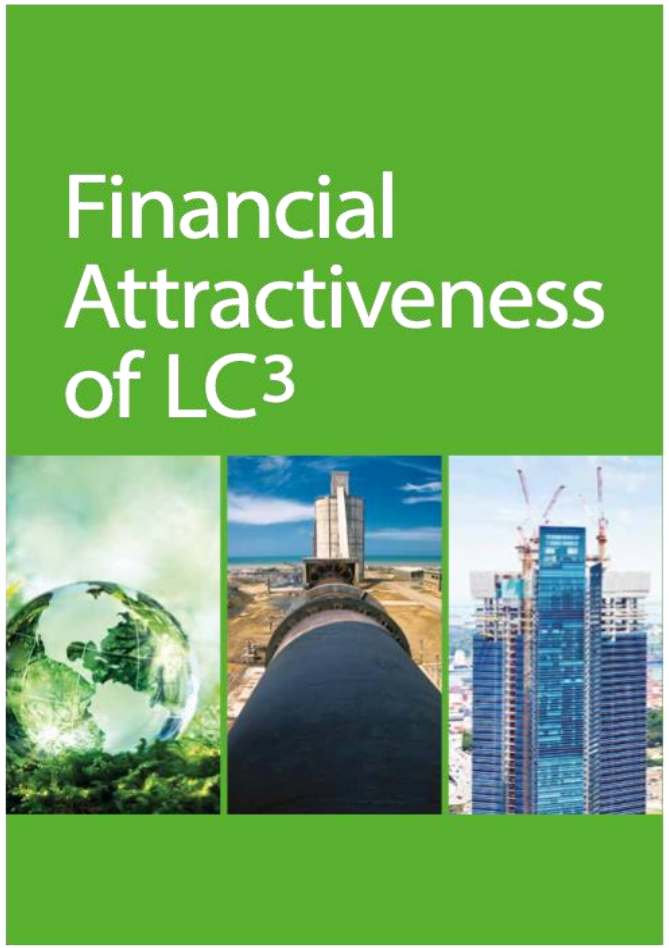
Limestone Calcined Clay Cement LC3

LOW CARBON LOW COST LOW CAPITAL

~~Lower~~ Reduced cost: Cementis study

~~降低~~减少成本：水泥研究





Report available: 报告可通过以下链接获得
https://lc3.ch/wp-content/uploads/2020/10/2019-LC3FinancialAttractiveness-WEB.pdf

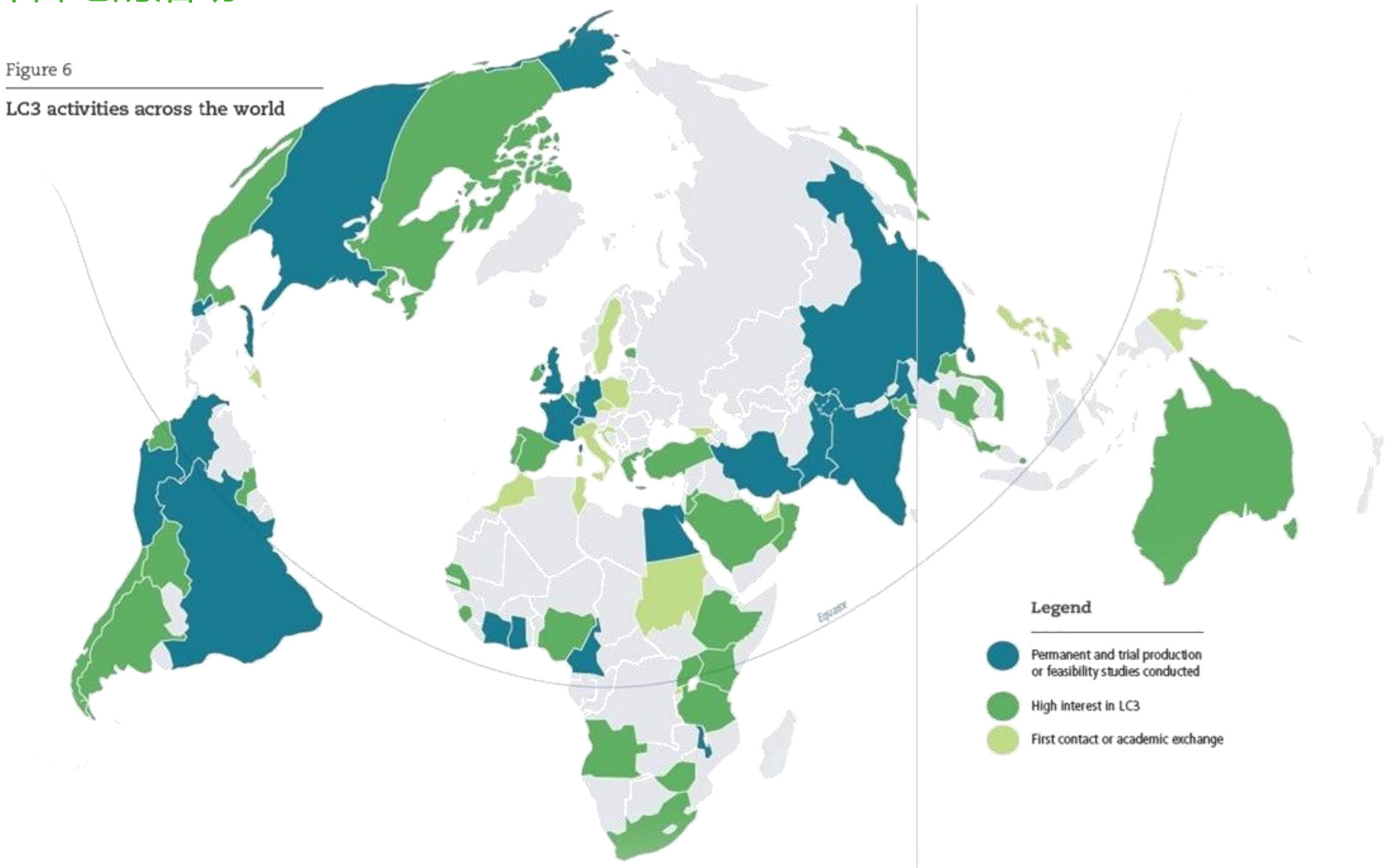
EPFL

LC3 activities across the world

LC3在世界各地的活动

Figure 6

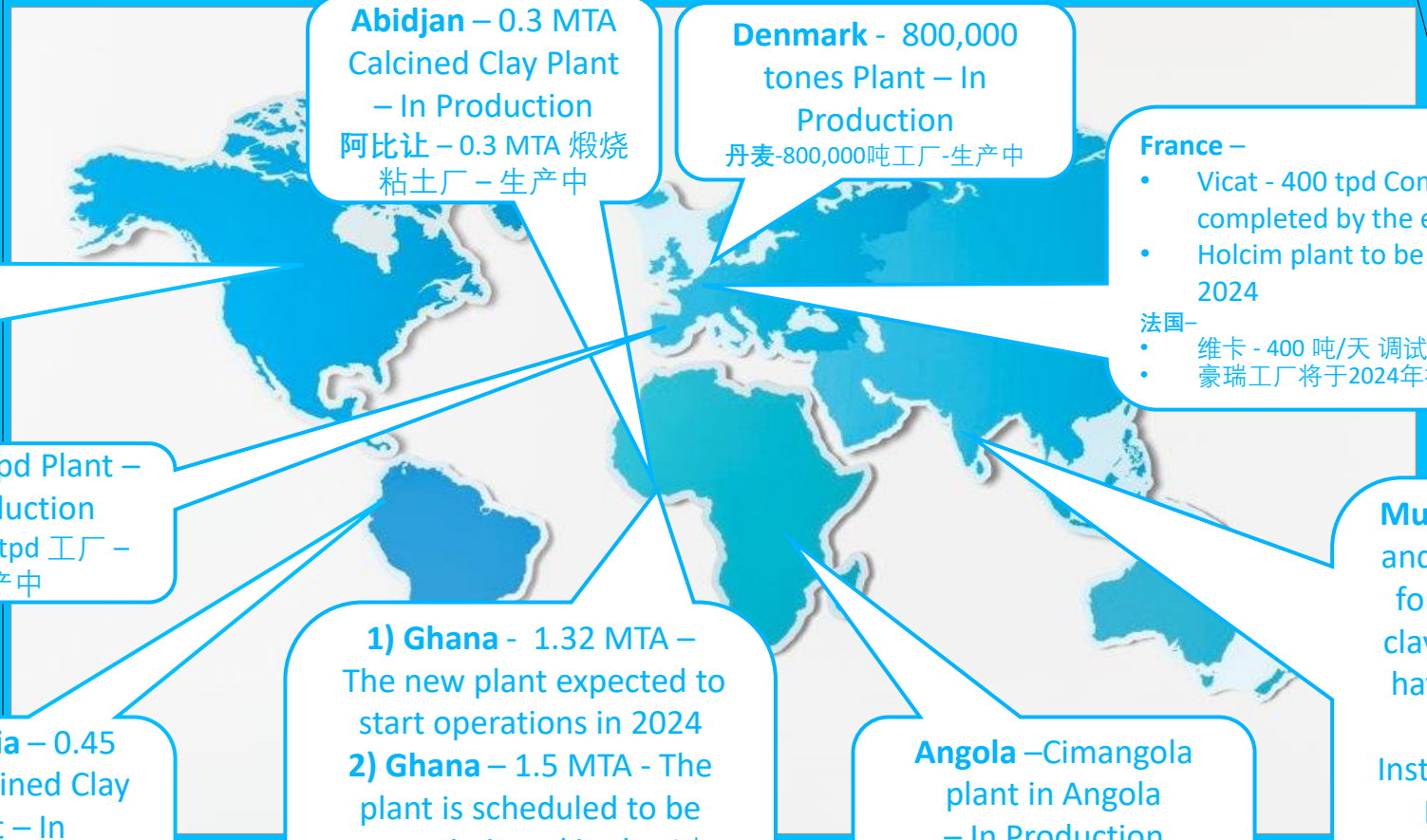
LC3 activities across the world



Global Cement and Concrete Association

Many projects announced around the globe 全球宣布的众多项目

CONCRETE FUTURE



Nebraska USA – Calcined Clay Plant – In Production Ash Grove
美国内布拉斯加州 – 煅烧粘土厂 – 生产中 灰树林

Abidjan – 0.3 MTA Calcined Clay Plant – In Production
阿比让 – 0.3 MTA 煅烧粘土厂 – 生产中

Denmark - 800,000 tones Plant – In Production
丹麦-800,000吨工厂-生产中

France –
- Vicat - 400 tpd Commissioning to be completed by the end of 2023
- Holcim plant to be commissioned by 2024

法国–
- 维卡 - 400 吨/天 调试将于 2023 年底完成
- 豪瑞工厂将于2024年投产

Spain - 4tpd Plant – In Production
西班牙 - 4tpd 工厂 – 生产中

Colombia – 0.45 MTA Calcined Clay Plant – In Production
哥伦比亚 – 0.45 MTA 煅烧粘土厂 – 生产中

1) Ghana - 1.32 MTA – The new plant expected to start operations in 2024
2) Ghana – 1.5 MTA - The plant is scheduled to be commissioned in the 1st Q23.
1） 加纳 - 1.32 MTA – 新工厂预计将于 2024 年开始运营
2） 加纳 – 1.5 MTA - 该工厂计划于23年第一季度投产。

Angola –Cimangola plant in Angola – In Production
安哥拉 – 安哥拉西曼戈拉工厂 – 生产中

Mumbai - In India ACC and Ambuja are at the forefront of calcined clay development and have begun a project with the Indian Institute of Technology Delhi to develop calcined clays.
孟买 - 在印度，ACC和Ambuja处于煅烧粘土开发的前沿，并已与德里印度理工学院开始开发煅烧粘土的项目。

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LOW CARBON LOW COST LOW CAPITAL

Substantial reductions in emissions ~80% could be achieved by working through the whole value chain

通过整个价值链的工作，可以实现约80%的大幅减排

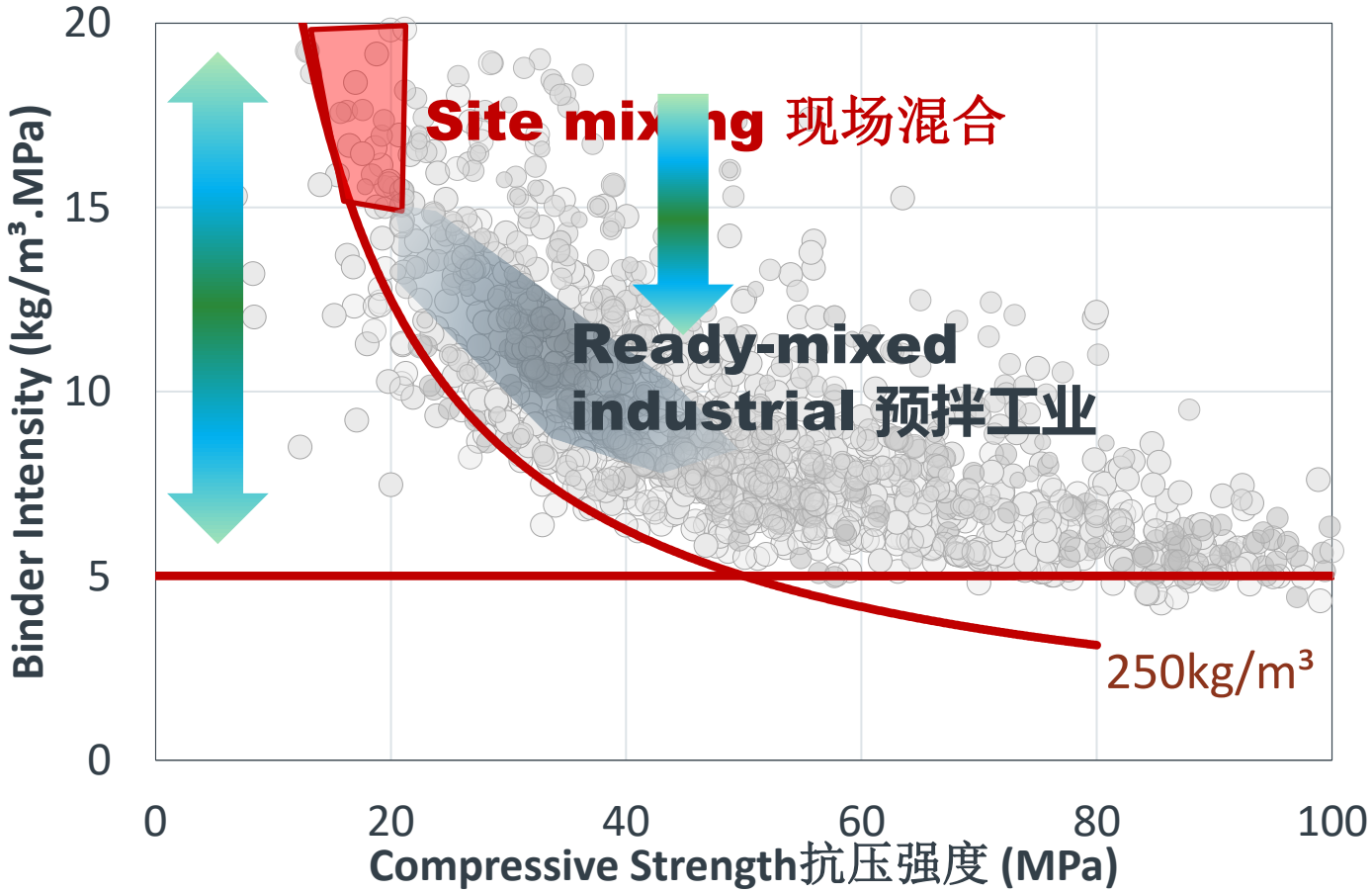
Few producers Quick wins implemented 少数生产商快速实现	Few producers Large remaining potential 少数生产商还有巨大的潜力	Many producers Implementation very difficult 多数生产商实施是非常困难	Chain of deciders Implementation very difficult 决策链实施非常困难	Big changes in mindset needed 需要思维方式的重大转变
Reduce CO_2 from clinker production 减少熟料生产中的碳排放	Reduce clinker in cement 减少水泥中的熟料	Reduce cement in concrete 减少水泥在混凝土中的用量	Reduce concrete in building 减少建筑内混凝土的用量	More efficient (re)use of buildings 更高效的利用建筑

SCMs

- Efficient plants 高效工厂
- Waste fuels 废弃燃料
- Alternate raw materials 可替代的原材料

- Aggregate grading 骨料分级
- Good admixtures 良好的外加剂
- Use filler 使用填充物

Efficiency of binder use (29 countries) 粘合剂使用效率（29个国家）



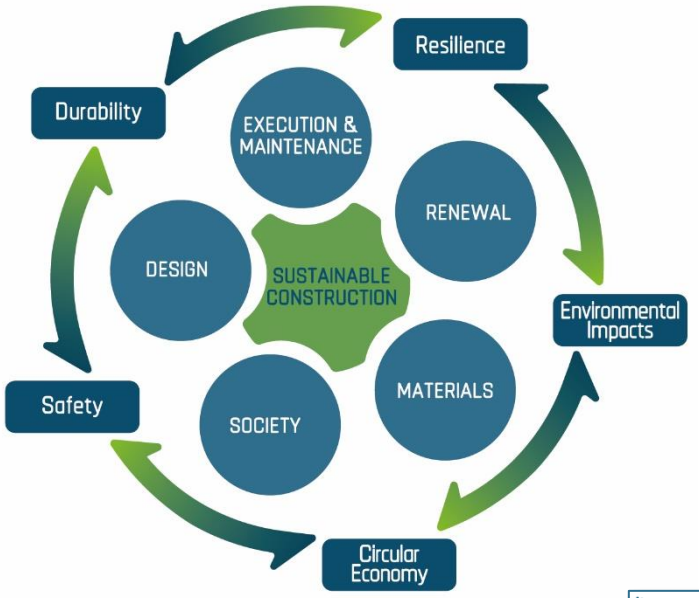
DAMINELI, et al. Measuring the eco-efficiency of cement use. **Cement and Concrete Composites**, 32, p. 555-562, 2010

Recommending a new paradigm for the built environment
为建筑环境推荐新范例

GLOBE

Global consensus on sustainability in the built environment
关于建筑环境可持续性的全球共识

- High level policy advice高级别政策咨询
- More than 150 nations 150+国家
- 5000+ experts 5000+专家
- 50+ years of expert networks 50+年专家网络
- Standards and guidelines 标准与准则
- Research and education 研究与教育
- Innovation 创新



www.globe-consensus.com

Limestone Calcined Clay Cement LC3

LOW CARBON LOW COST LOW CAPITAL

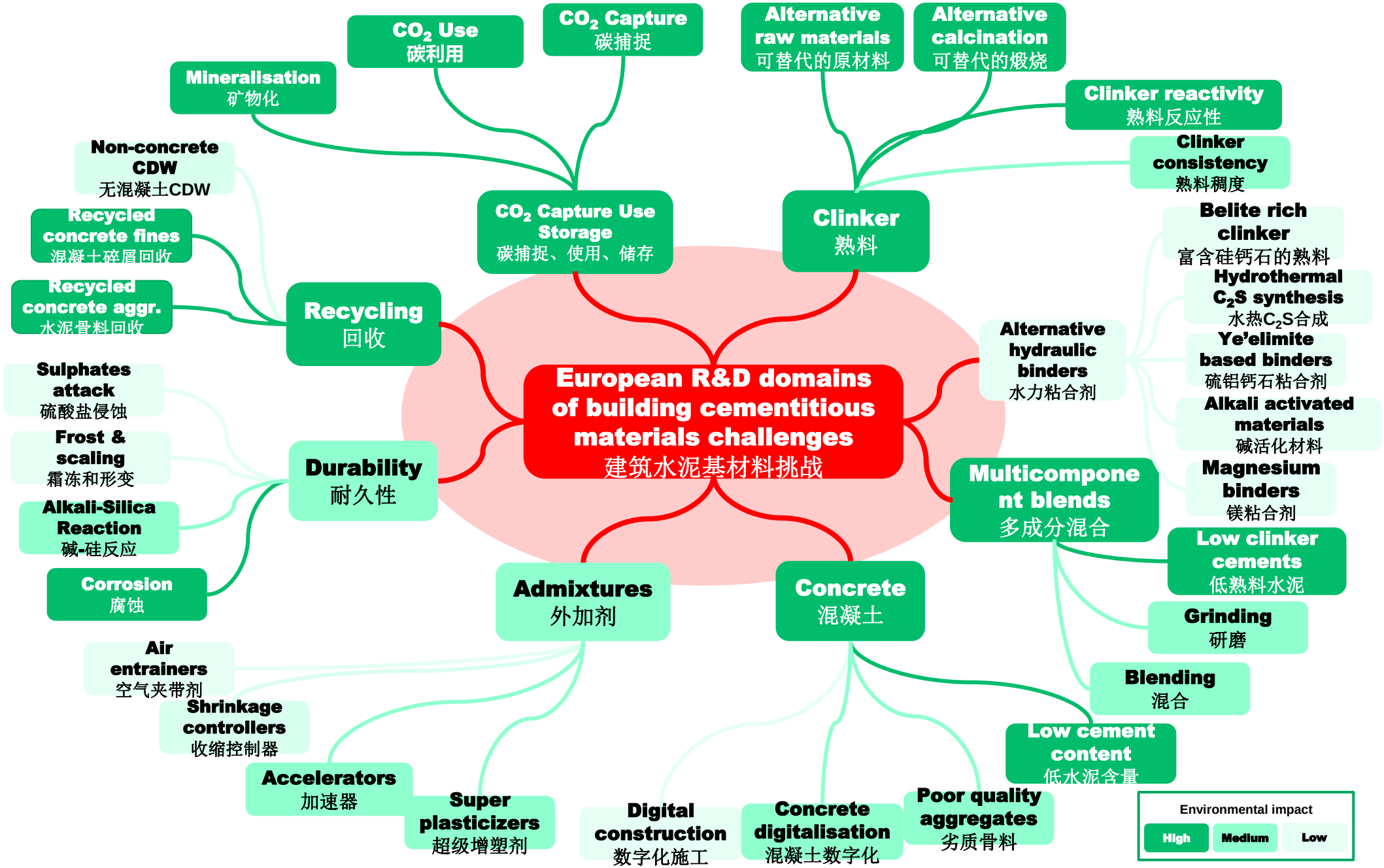
Research needs for Cementitious Materials: forthcoming paper in Rilem Technical Letters

水泥基材料的研究需求可以参见即将发表在Rilem Technical Letters的论文

Karen Scrivener, EPFL Switzerland
Mohsen Ben Haha, Heidelberg Cement
Christophe Levy, Holcim
Patrick Juilland, Sika

EPFL LMC

Watermelon: and 30 key questions 思维导图：30个关键问题



Concluding remarks 综上所述

- Substantial reductions in CO2 possible 大幅度减少二氧化碳排放
  - At cement level by increasing SCM substitution 在水泥层面，提高SCMs的替代量
  - At concrete level by minimising cement content 在混凝土层面，尽量减少水泥含量
  - At structure level 在建筑层面
- All of the above will also lower cost 上述所有措施也将降低成本
- Remainder CO_2 can only be dealt with by carbon capture and storage high cost, infrastructure not in place. 剩余的二氧化碳只能通过碳捕捉和存储来处理。但成本高，且基础设施还不到位。
- Calcined clays are the only realistic option for extending the use SCMs

  煅烧粘土是延长SCMs使用的唯一现实的选择
- Can be done **FAST** and at **SCALE** 能快速并大规模的实现

Limestone Calcined Clay Cement

LC3

www.LC3.ch

9th Doctoral School LC3

LC3第九届博士论坛

6th – 9th February 2023

2023年2月6日至9日

École polytechnique fédérale de Lausanne

Switzerland 瑞士洛桑联邦理工学院

Schweizerische Eidgenossenschaft
Confédération suisse
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Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

EPFL

LABORATORY OF CONSTRUCTION MATERIALS

Thank you

More information on: www.LC3.ch

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