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ENGINEERING & THE BUILT ENVIRONMENT

Concrete Materials & Structural Integrity Research Unit

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CONCRETE SOCIETY OF SOUTHERN AFRICA

LOW-CARBON BINDERS AND CONCRETES, WITH A VIEW TO THEIR DURABILITY AND ADOPTION IN CONSTRUCTION PRACTICE

Mark Alexander, UCT

(Acknowledgements to colleagues & students)

Concrete Materials & Structural Integrity Research Unit

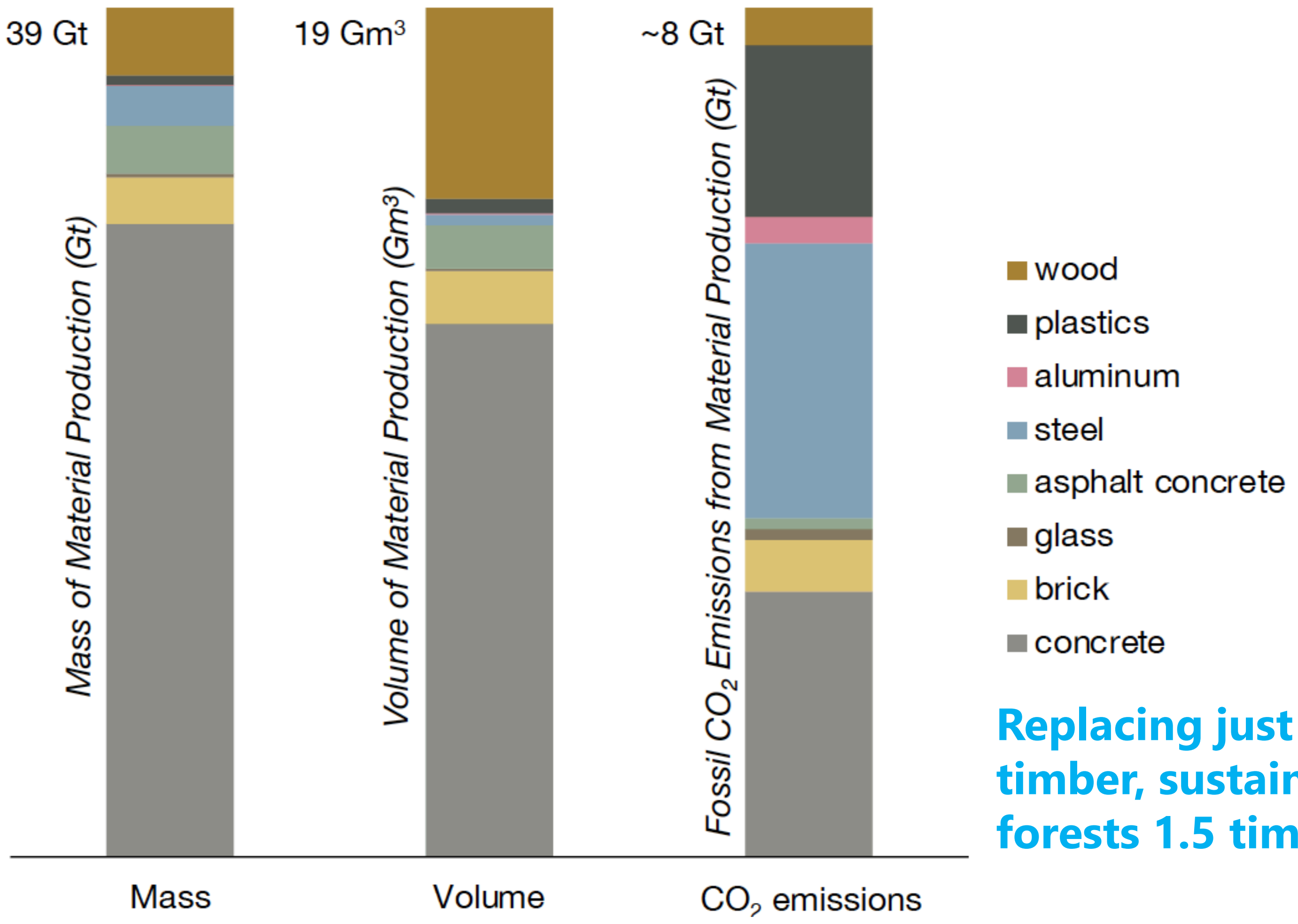
University of Cape Town

OUTLINE

- Introduction; Resources
- Motivation & Background
- Low carbon binders
- Durability Concerns
- Standards & Policies
- Closure

RESOURCES

World use of materials: what mankind makes every year



Submitted to Nature Climate Communications

90% in construction

75% is 'concrete'

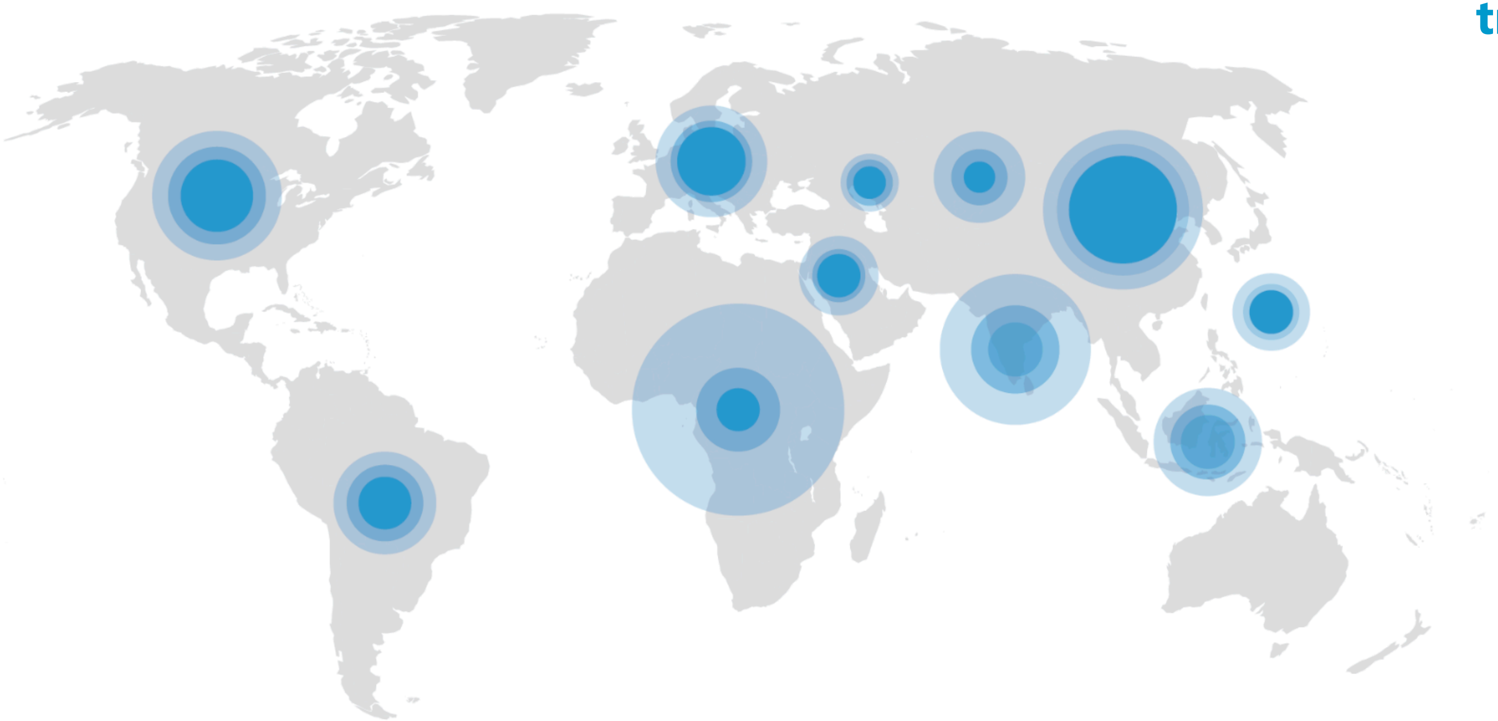
(cement-based materials)

Replacing just 25% of concrete with timber, sustainably, would require new forests 1.5 times the size of India.

Slide courtesy of F Zunino, UC Berkeley

Engineers and scientists are called to action

Global building floor area
is expected to **double** by 2060.



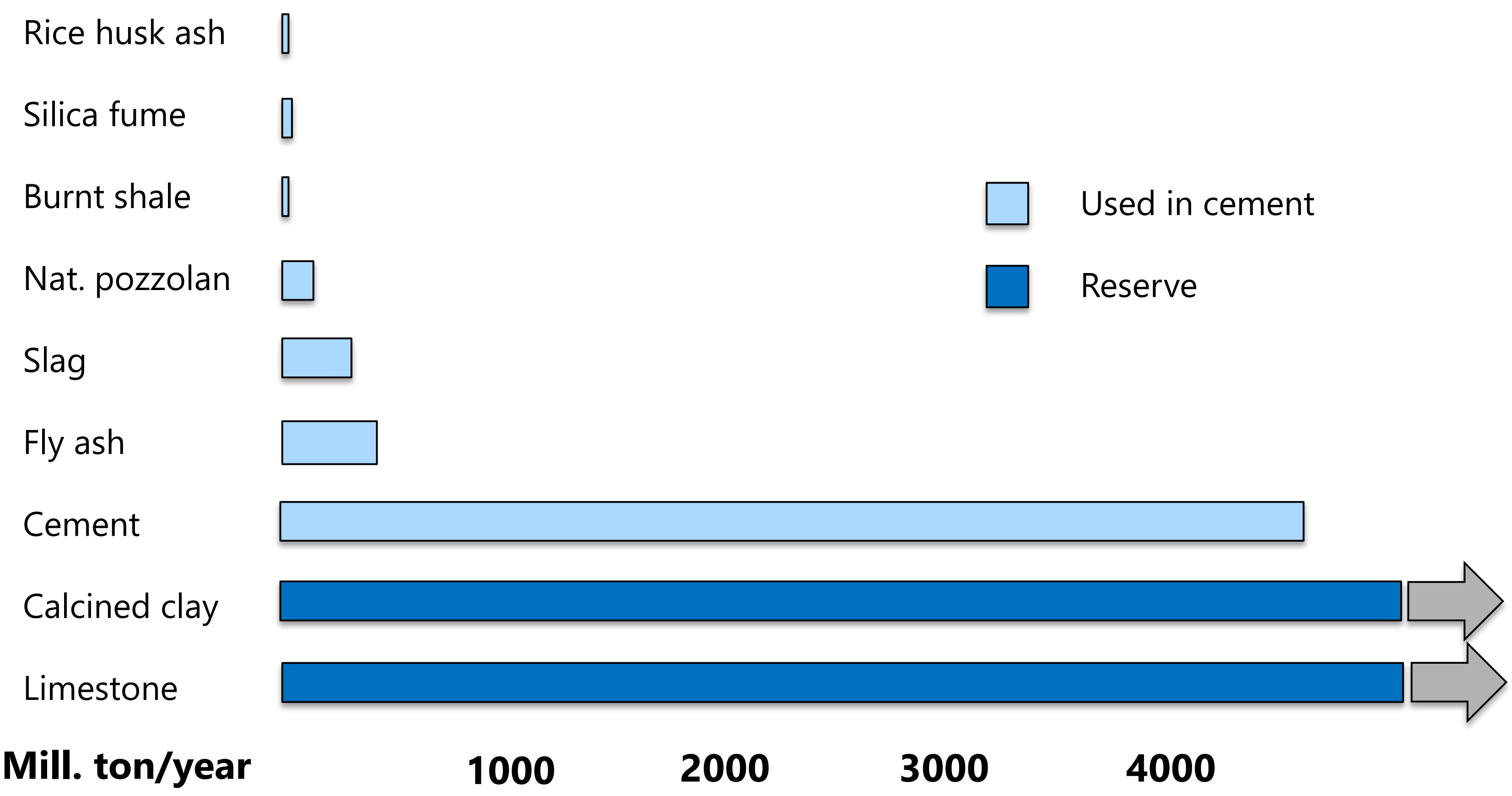
Data Sources: Global ABC, Global Status Report 2017

Difference between solid and translucent circles represent estimated current building floor deficit

Slide courtesy of F Zunino, UC Berkeley

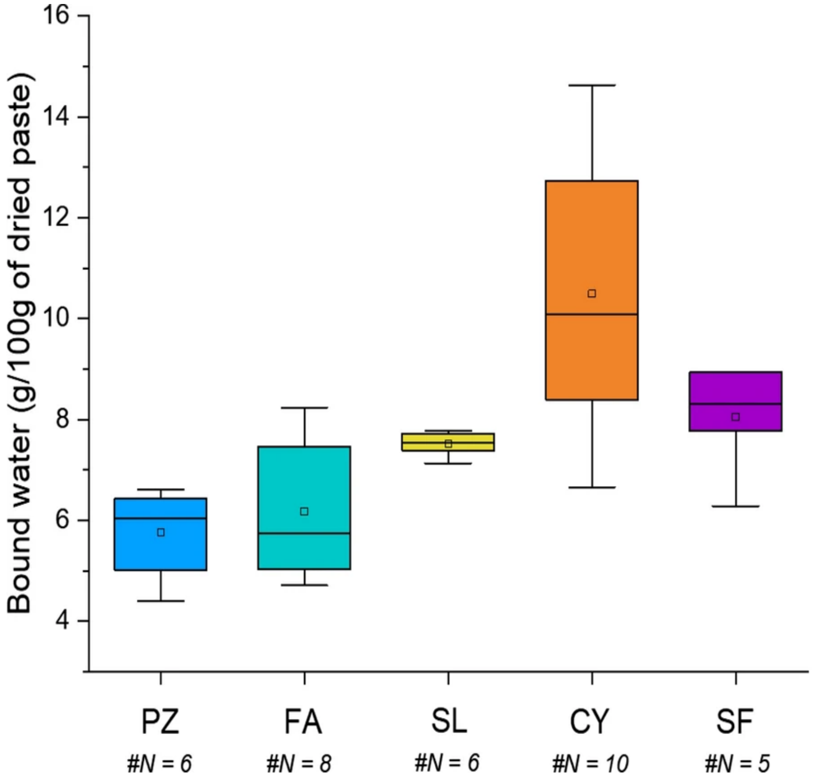
Use of cement-based materials: availability and reactivity

Availability argument



(UNEP, 2016)

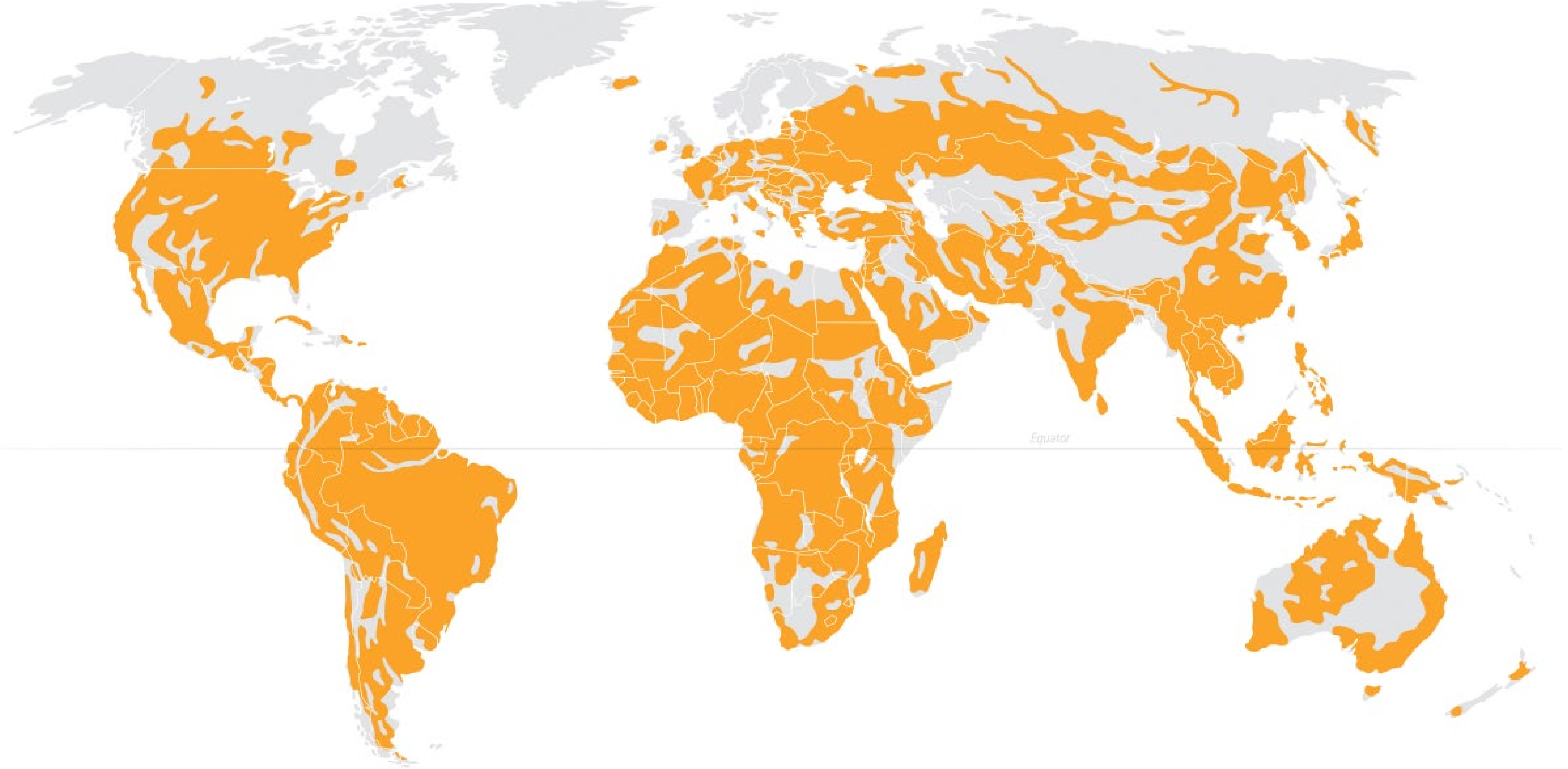
Reactivity argument



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

Slide courtesy of F Zunino, UC Berkeley

Distribution of kaolinitic (1:1) clay resources



Slide courtesy of F Zunino, UC Berkeley

Source: Ito and Wagai, Scientific data 2017

LIMESTONE DEPOSITS IN AFRICA

Slide courtesy of V Adeoye, CoMSIRU, UCT

Limestone Deposits in Africa

7/3/2025

Limestone Deposits in Africa

- Algeria
- Libya
- Egypt
- Malawi
- Mozambique
- Namibia
- Nigeria
- South Africa
- Uganda
- World_Hillshade

1:36,271,380

0 415 830 1,660 mi

0 500 1,000 2,000 km

Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community, Esri, USGS

DEFINITIONS

"LOW-CARBON BINDERS AND CONCRETES, WITH A VIEW TO THEIR DURABILITY AND ADOPTION IN CONSTRUCTION PRACTICE"

DEFINITIONS:

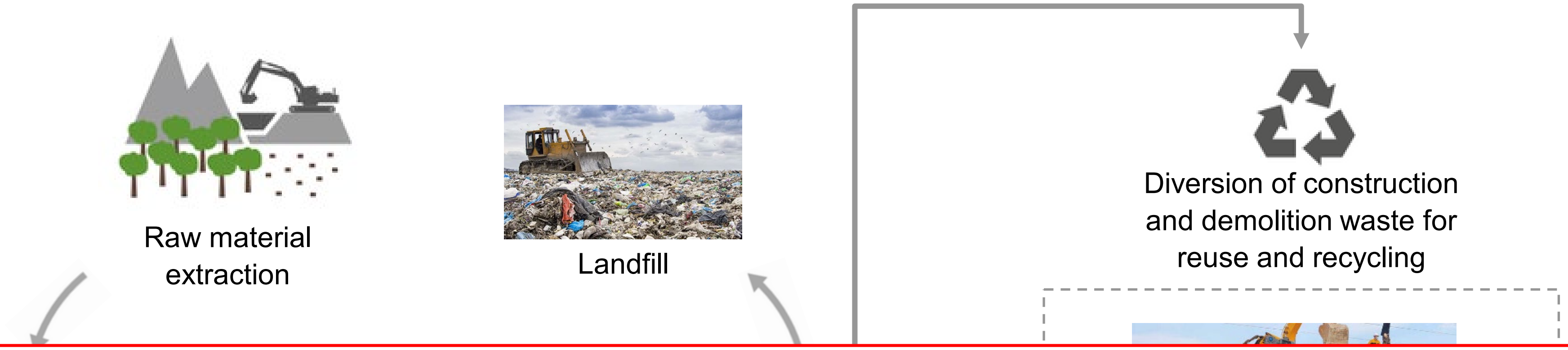
"Durability"*:** "the ability of a structure or component to withstand the design environment over the design life, without undue loss of serviceability or need for major repair" (ASTM E632-82* 1988**).

THUS: Durability

- relates to the concept of material performance; not a purely intrinsic property.
- relates to the dominant deterioration mechanism and exposure environment.

"Low-carbon binders": binders with significantly lower carbon footprint than traditional PC, achieved via use of SCMs (incl. LC^3), other alternative binders, AAM etc.

(Caveat: must have a total lower carbon footprint in the finished product!)

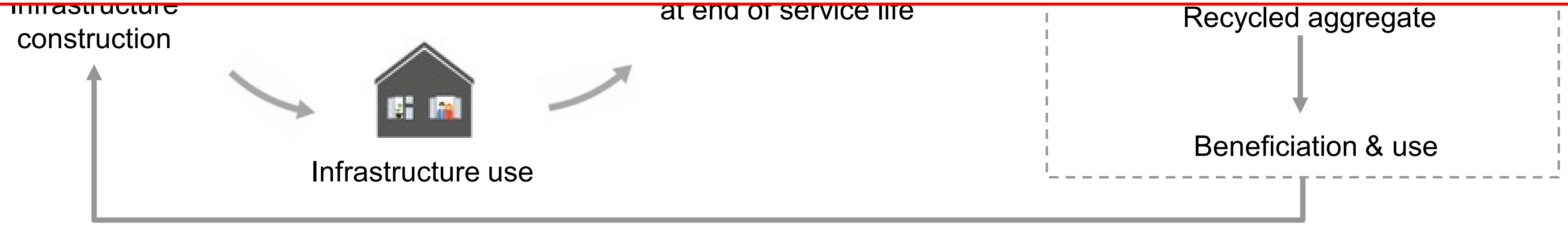


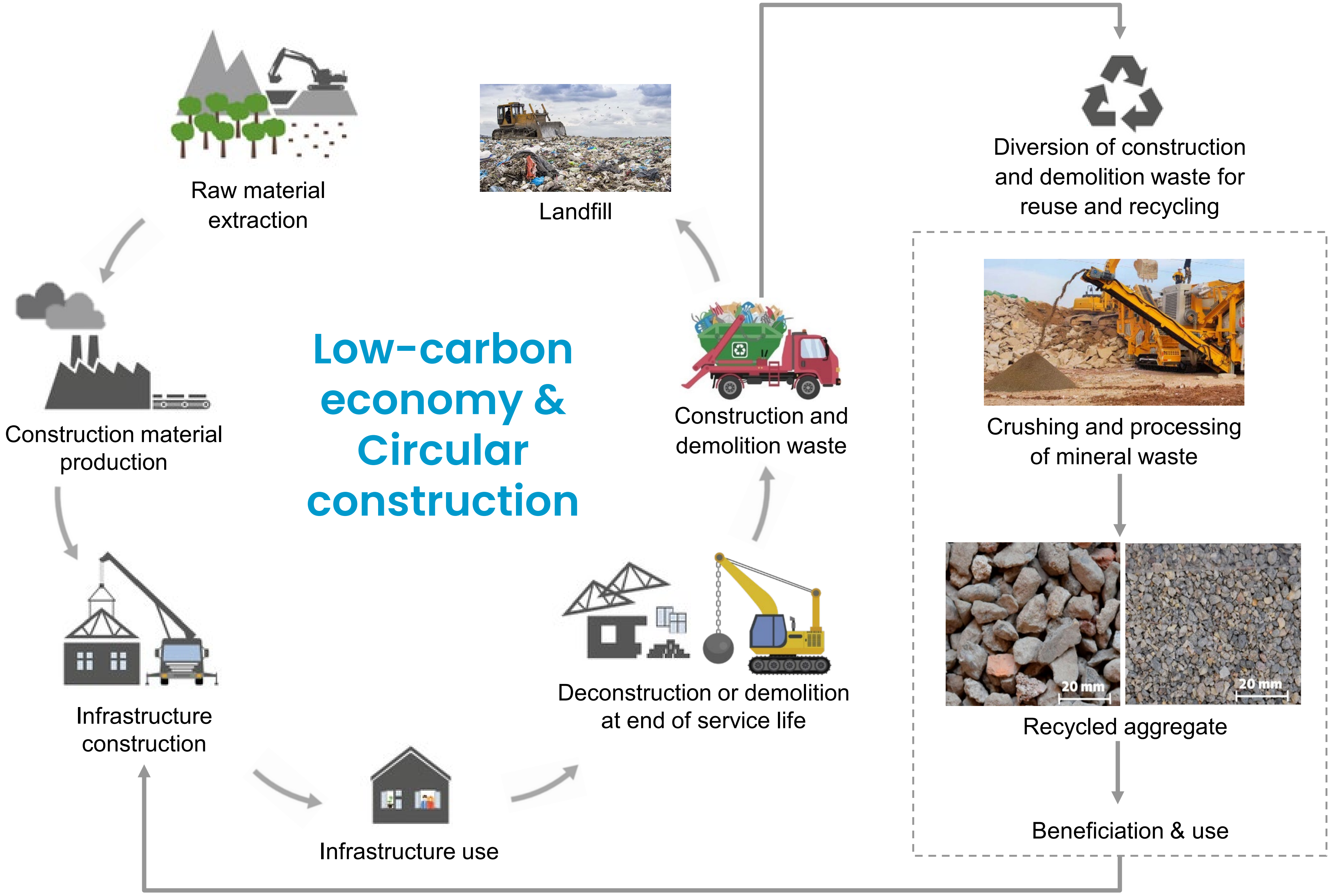
CIRCULAR ECONOMY DEFINITION:

"The circular economy is a multi-level resource use system that stipulates the complete closure of all resource loops. Recycling and other means that optimize the scale and direction of resource flows contribute to the circular economy and its supporting practices and activities.

In its conceptual perfect form, all resource loops will be fully closed.

In its realistic imperfect form, some use of virgin resources is inevitable."




Low-carbon economy & Circular construction
Raw material extraction
Landfill
Diversion of construction and demolition waste for reuse and recycling
Construction material production
Construction and demolition waste
Crushing and processing of mineral waste
Infrastructure construction
Deconstruction or demolition at end of service life
20 mm
20 mm
Recycled aggregate
Infrastructure use
Beneficiation & use

MOTIVATION AND BACKGROUND

Low-carbon binders

- Not actually 'new', e.g. slag cements in Europe, SA etc. used for 60+ yrs (E.g. Fulton 1969; work of Mills and others.)
- Highly extended cements (e.g. slag ≥ 70%) used, provided properties understood.
- Have in many instances shown admirable durability.

Concrete is, in reality, a low-carbon material!

E.g. c. 90-200 kg $CO2_e$/ton). Steel 2735 kg $CO2_e$/ton.

BUT: for 'novel' binders, essential information is needed on properties and use.

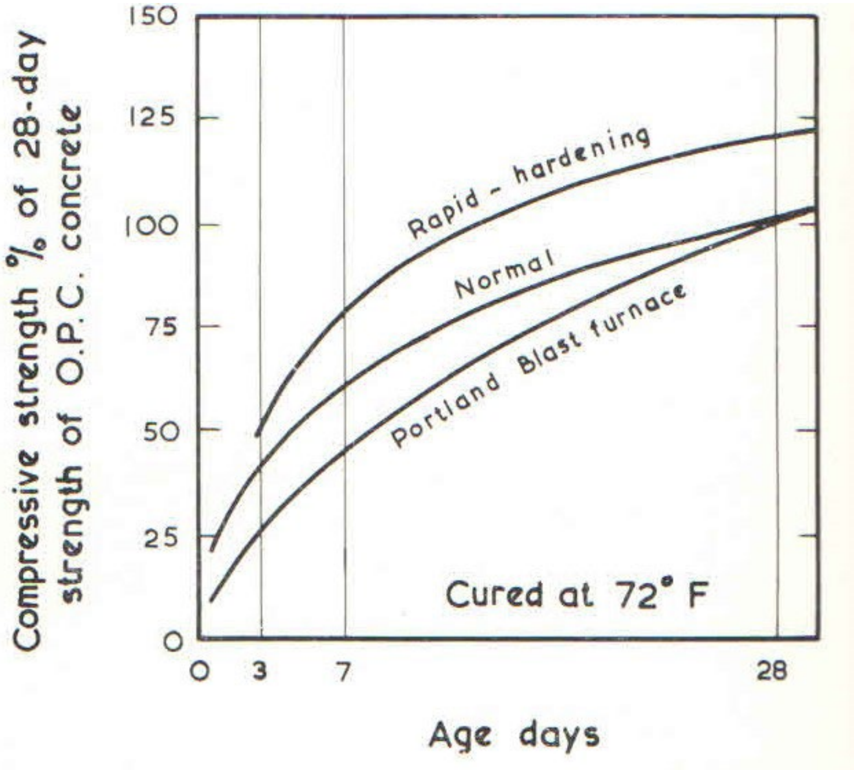


FIG. 7.7.—Effect of Cement Type on the Compressive Strength of Concrete.

Source: Fulton's Concrete Technology, 4th edn (1969)

Slags and FAs slowly being phased out in the medium-term.

MOTIVATION AND BACKGROUND

KEY QUESTIONS:

What are the essential challenges in getting new information and applications of low-carbon cements/concretes into practice?

What actions are needed in this area?

What will be the effect of climate change? Higher temps, lower RHs, greater rates of deterioration?

MOTIVATION AND BACKGROUND

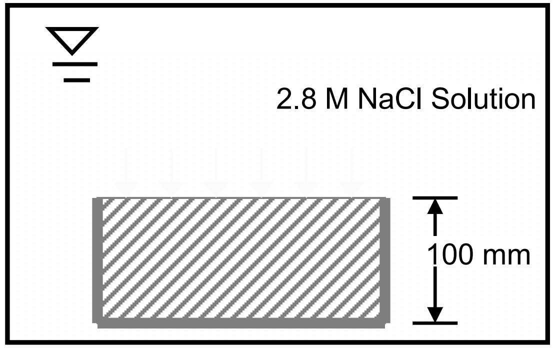
SUGGESTED PATHWAYS
Importance of fundamental research

↓

Need to carry out work on concrete, not just pastes and mortars
Field applications – need for demonstration projects that 'prove' the viability of the systems

↓

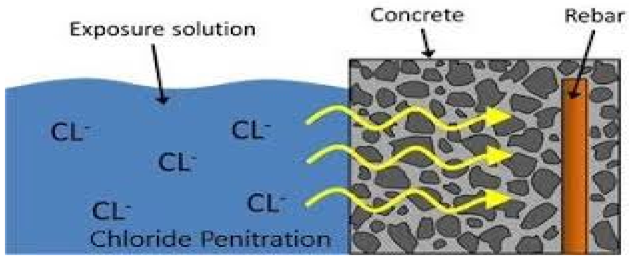
Policies & Standards: e.g. materials and construction specifications and appropriate standard test methods
Others, e.g. academic / industry collaborations



DURABILITY AND LOW–CARBON BINDERS

WHAT DURABILITY ISSUES MIGHT BE EXPECTED WITH LOW-CARBON BINDERS / CONCRETES?

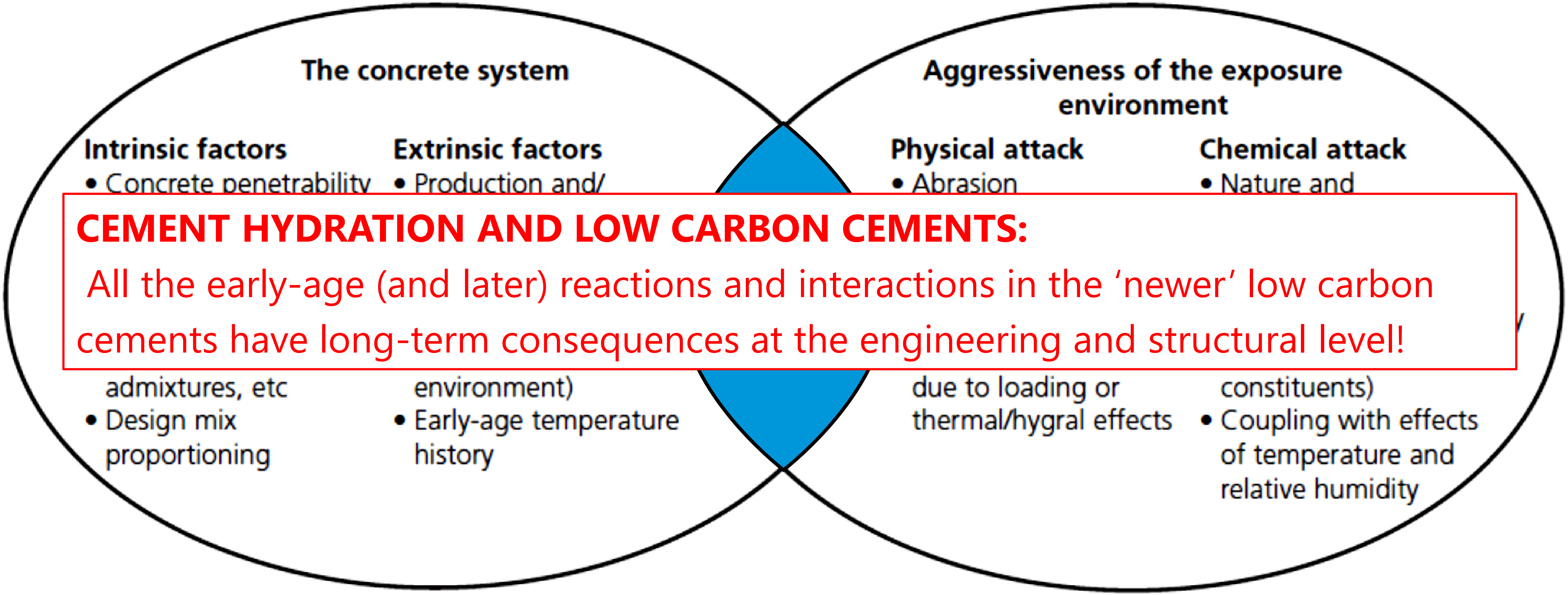
- Rapid carbonation – but this is not *per se* a durability problem!
- microstructural changes with time, e.g. from ingress of agents, effect of environment; changes of phase assemblages, etc.
- Issues where alkalinity residual is essential, e.g. carbonation, soft water attack, ….
- Early strength issues
- Non-robust systems
- etc. etc.



Durability requires both *chemical* durability and *physical* durability: i.e. understanding of chemistry and physics, in relation to transport properties:

- impenetrability ('tightness') of microstructure; changes in microstructure with aging and effects such as carbonation, and
- chemical interactions with products of hydration; e.g. 'buffering' aspects for CO_2 and chlorides; lower alkalinity; lower CH residual; soft water; sulphates
- 'Competition' between these two aspects

DURABILITY: CONSIDER THE CONCRETE – EXPOSURE SYSTEM

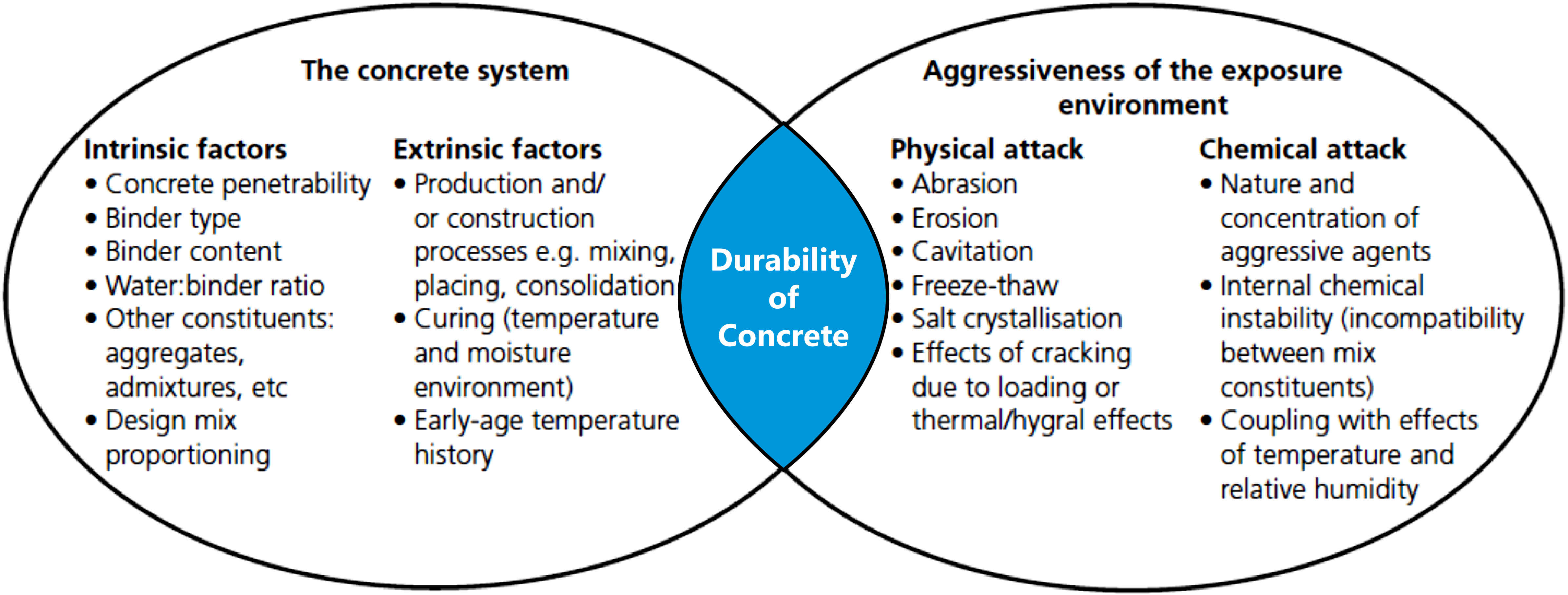


CEMENT HYDRATION AND LOW CARBON CEMENTS:

All the early-age (and later) reactions and interactions in the 'newer' low carbon cements have long-term consequences at the engineering and structural level!

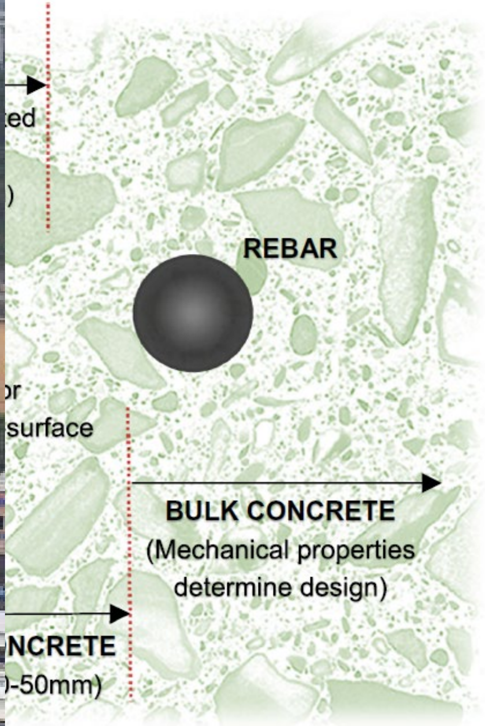
Source: Fulton's Concrete Technology, 10th edn (2021)

DURABILITY: CONSIDER THE CONCRETE – EXPOSURE SYSTEM



Source: Fulton's Concrete Technology, 10th edn (2021)

CORROSION OF RC STRUCTURES

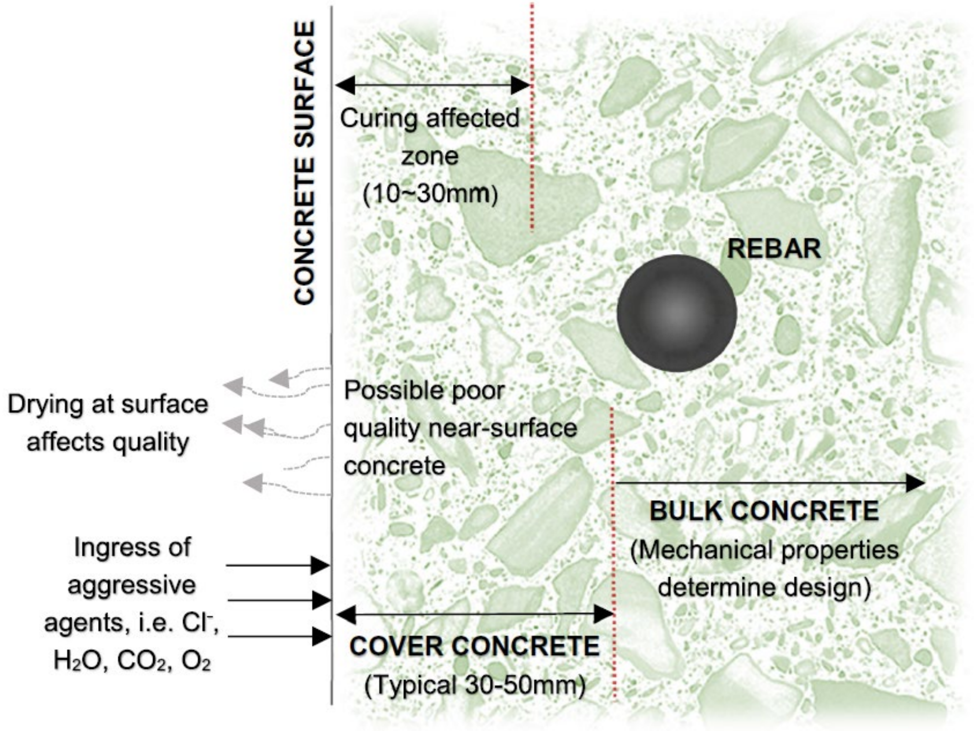


CORROSION OF RC STRUCTURES

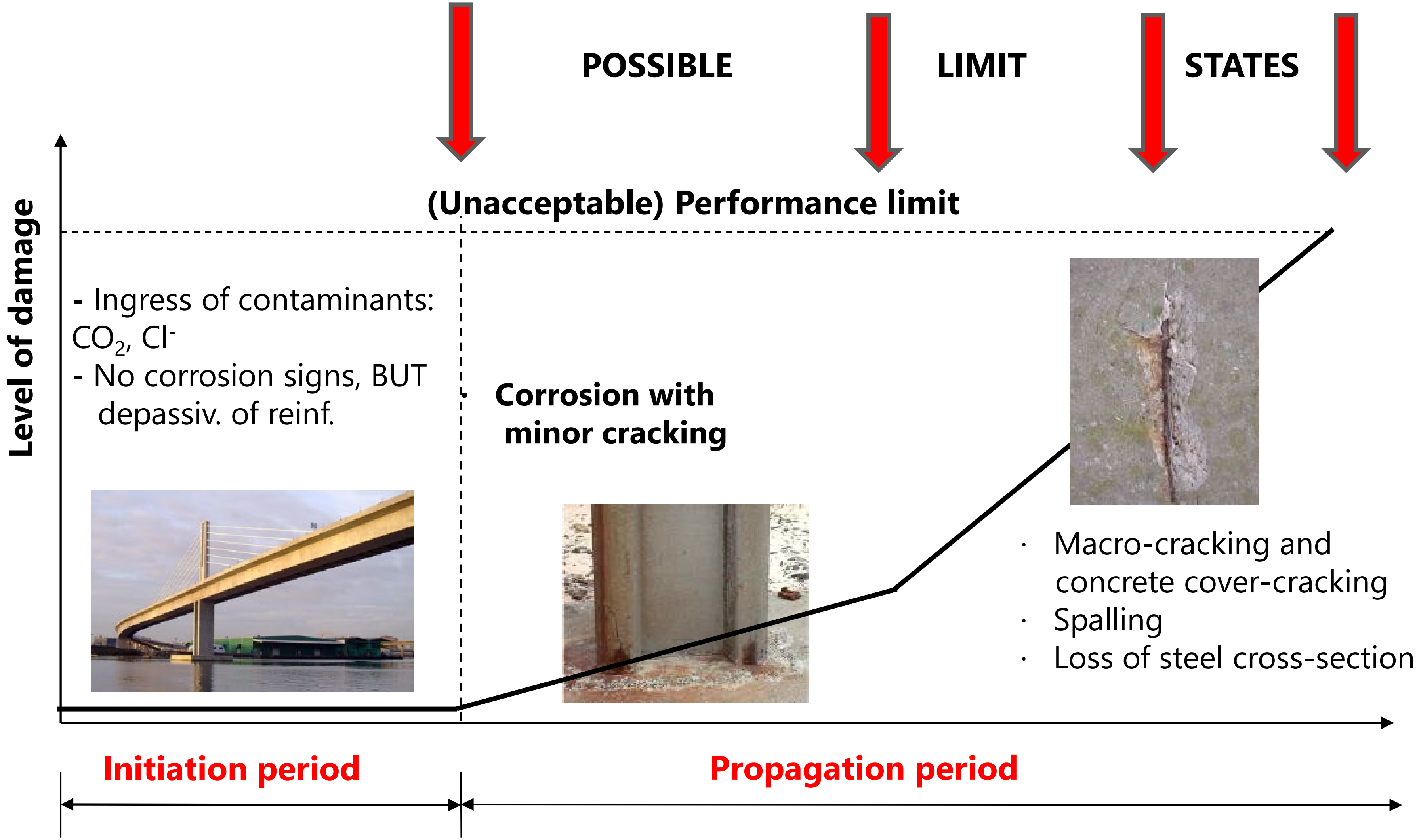
- This is the overriding concern.
  - ➢ August 2018 Morandi Bridge collapse in Genoa

CORROSION OF REINFORCING STEEL

- **In PC systems:**
  - Generally high alkalinity reserve, which may be depleted with time (e.g. carbonation)
  - Has limited binding abilities for certain ions (e.g. Cl^-)
  - And, lower resistivity can be a factor
- **In low-carbon systems:**
  - May be less robust, i.e. more sensitive to processing techniques and environment, e.g. temp.
  - May offer better resistance to aggressive ions
  - Generally lower alkalinity - may be an advantage (e.g. AAR)



DURABILITY: CORROSION / DAMAGE PROGRESSION

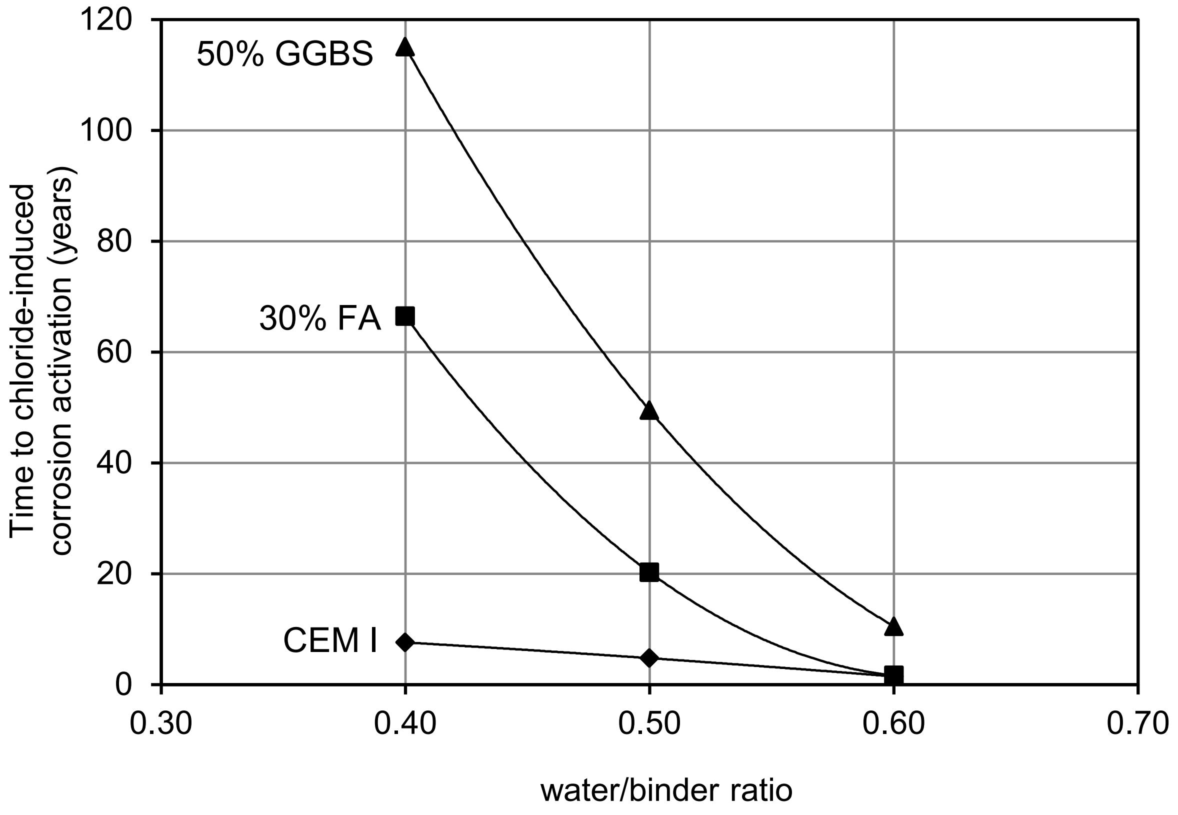


Limit states:

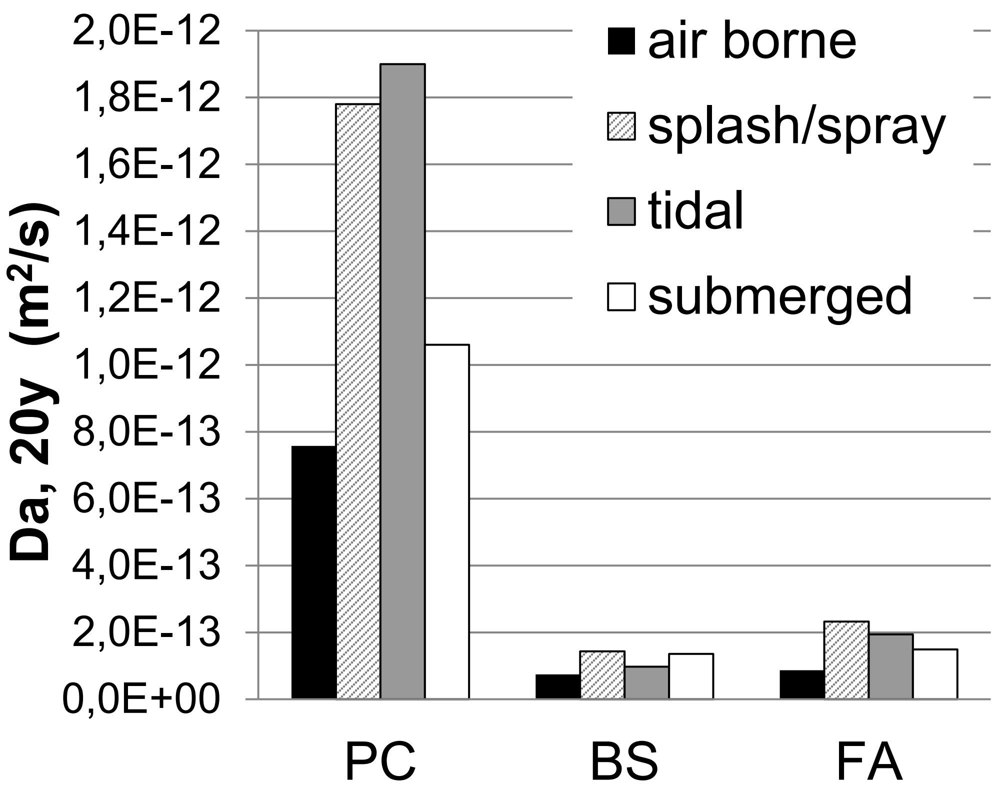
1. Depassivation of reinforcement
2. Crack formation
3. Concrete spalling
4. Possible collapse via bond failure or reduction of steel cross-section

LOW-CARBON BINDERS: a) CHLORIDES

Chlorides: In general, low-carbon binders give improved chloride resistance: improved microstructure (physical impenetrability) and appropriate hydrates for binding.

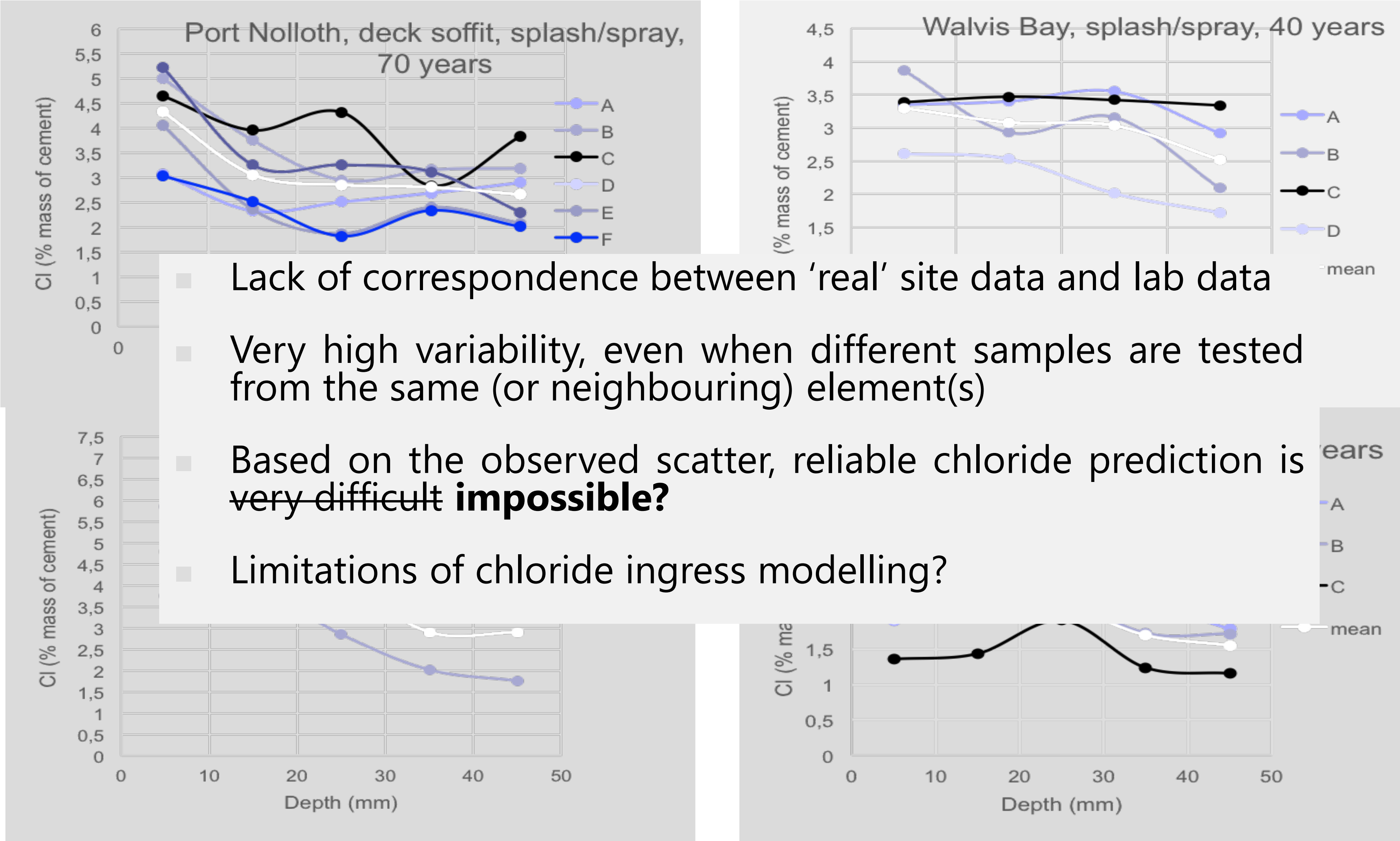


Source: Fulton's Concrete Technology, 10th edn (2021)



Source: PhD Thesis, Heiyantuduwa, UCT 2021

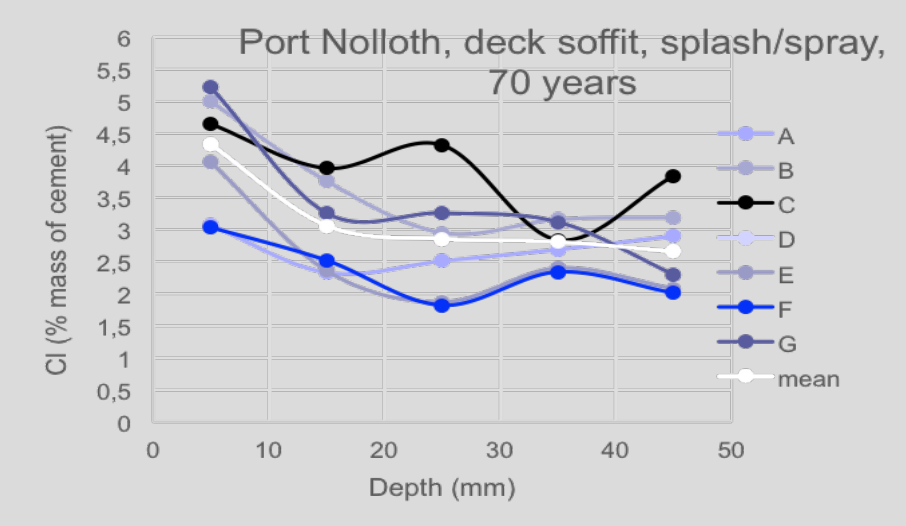
CRITIQUE OF CHLORIDE-INGRESS MODELLING
LONG-TERM CHLORIDE DATA, REAL STRUCTURES

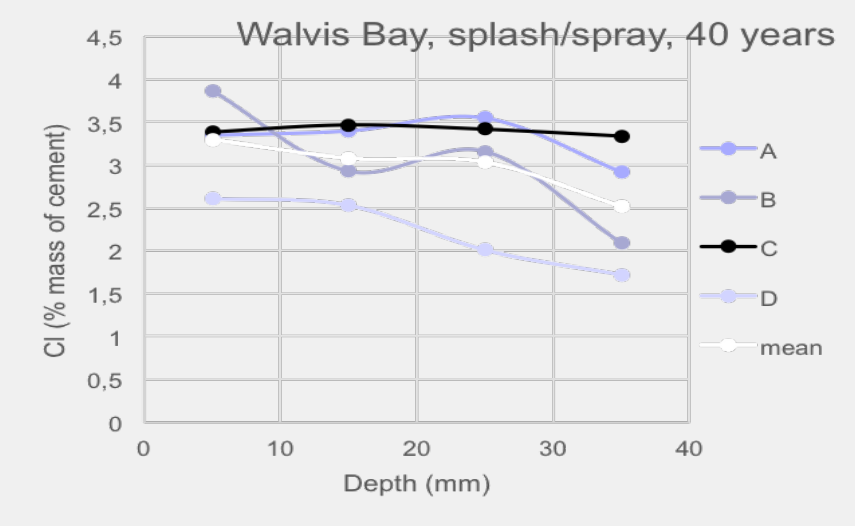


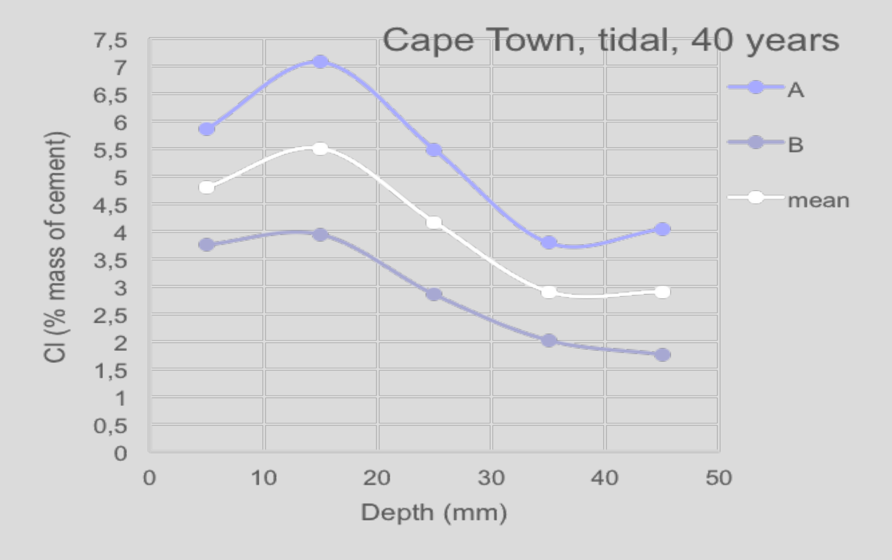
- Lack of correspondence between 'real' site data and lab data
- Very high variability, even when different samples are tested from the same (or neighbouring) element(s)
- Based on the observed scatter, reliable chloride prediction is ~~very difficult~~ **impossible?**
- Limitations of chloride ingress modelling?

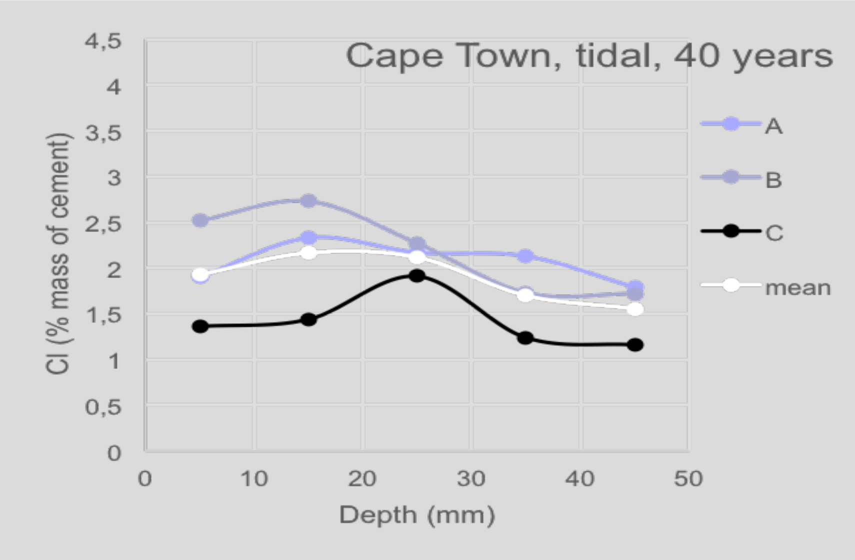
CRITIQUE OF CHLORIDE-INGRESS MODELLING

LONG-TERM CHLORIDE DATA, REAL STRUCTURES





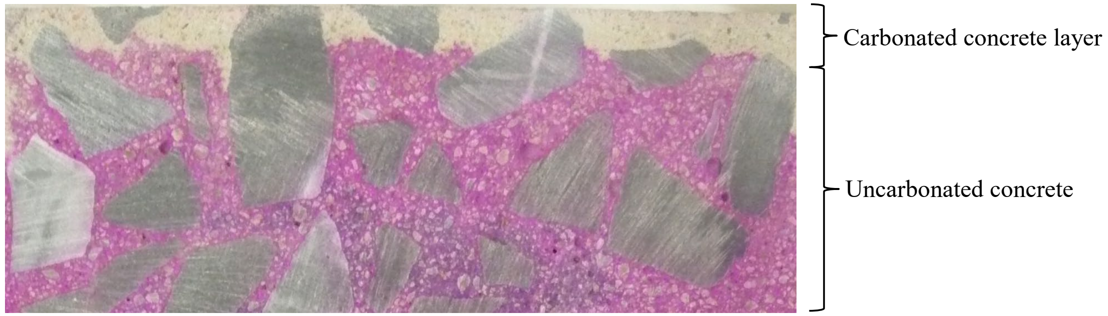




LOW-CARBON BINDERS: b) CARBONATION

Carbonation

- **In PC systems:**
  - Before carbonation: high CH content: 'buffer' against CO_2 ingress.
  - After carbonation: calcium carbonate precipitation: porosity reduction and pore refinement (but depends on w/c ratio).

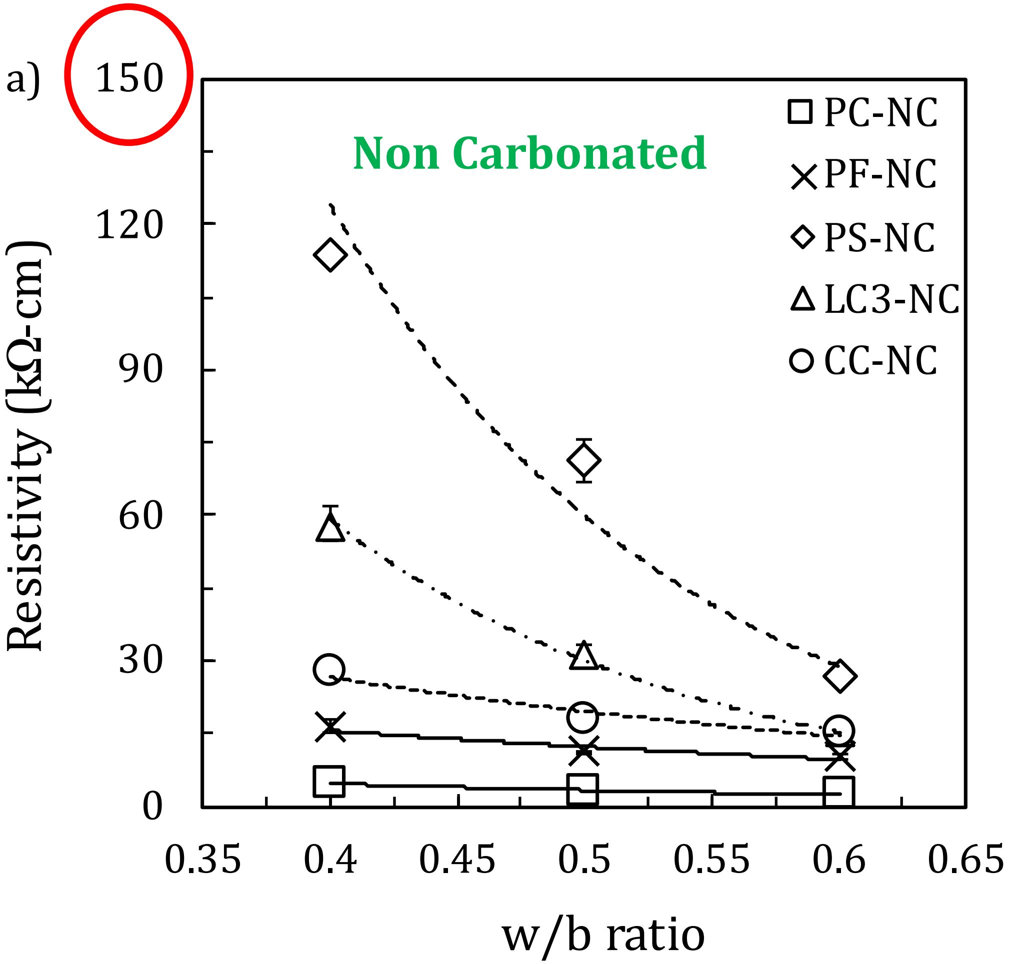


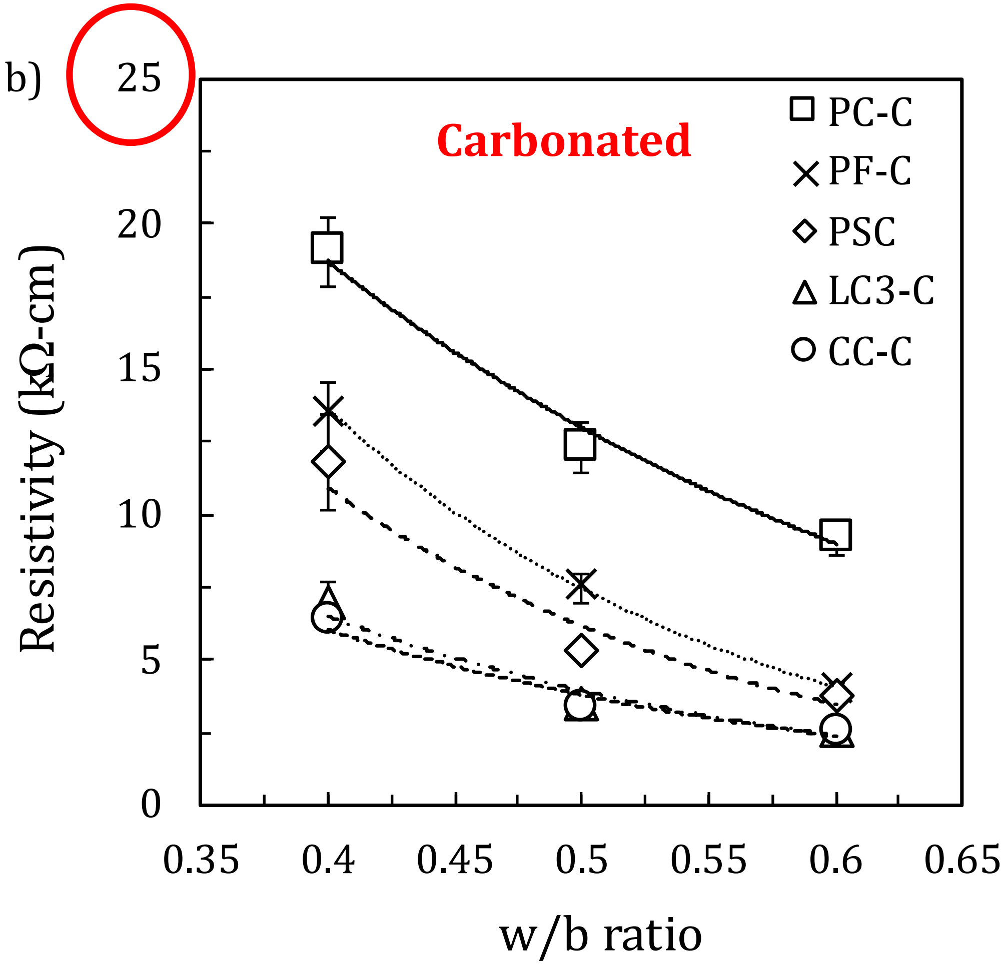
- **In low-carbon systems:**
  - Before carbonation, lower critical and threshold pore diameters, i.e. refined pore structure; pozzolanic space-filling reactions.
  - After carbonation: coarsened pore structure, higher connectivity, reduced interaction of transporting media with pore surfaces. What effects? Resistivity? See next slide.

LOW-CARBON BINDERS: ISSUE OF RESISTIVITY

Carbonation: PC systems vs low-carbon systems: resistivity of carbonated vs uncarbonated binders

Details: 3% CO_2, 60% RH, 27 °C, 6 mth – 'fully' carbonated mortars, accelerated carbonation.





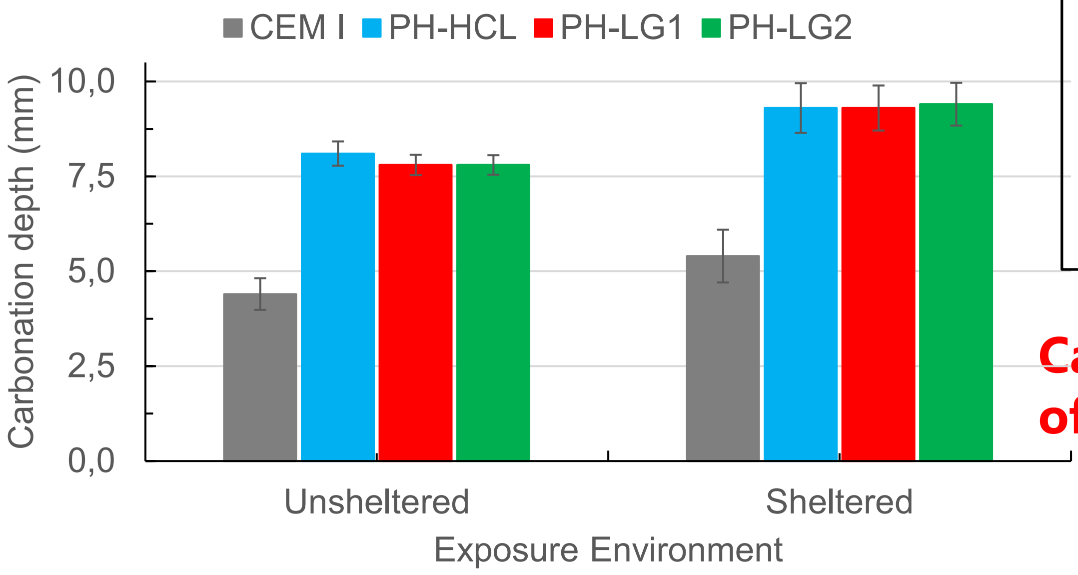
Lupesh PhD Thesis, 2025 @ IIT Delhi under Prof. Shashank Bishnoi

Carbonation: PC systems & low-carbon systems: resistivity of carbonated vs uncarbonated binders (LC^3)

Natural Carbonation

Concrete Samples

w/b = 0.6

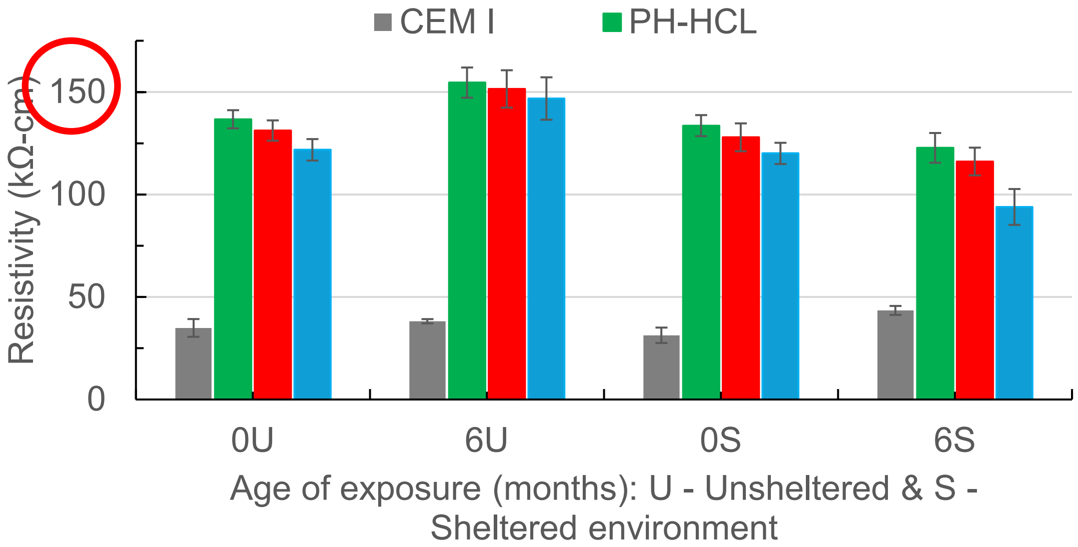


Carbonation of concrete, 6 months of exposure

Limestone (L): $CaCO_3$ content:

HCL ≈ 89%
LG1 ≈ 82%
LG2 ≈ 59%

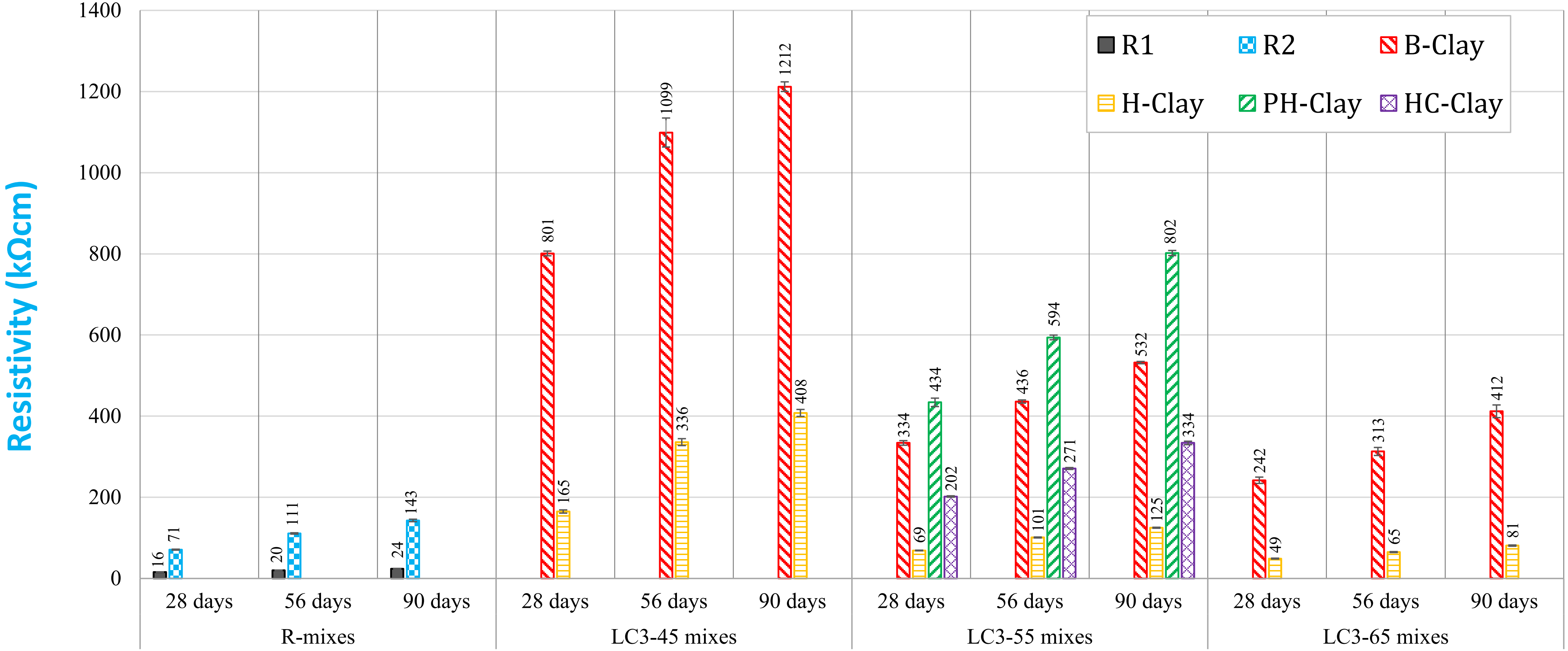
Clay kaolinite content:
PH (Pugu Hard) ≈ 51%



Evolution of concrete surface resistivity with carbonation exposure (6 months)

Kilumile PhD Thesis, 2025 @ UCT under Prof. Mark Alexander

FURTHER RESISTIVITY RESULTS – LC^3 CONCRETES



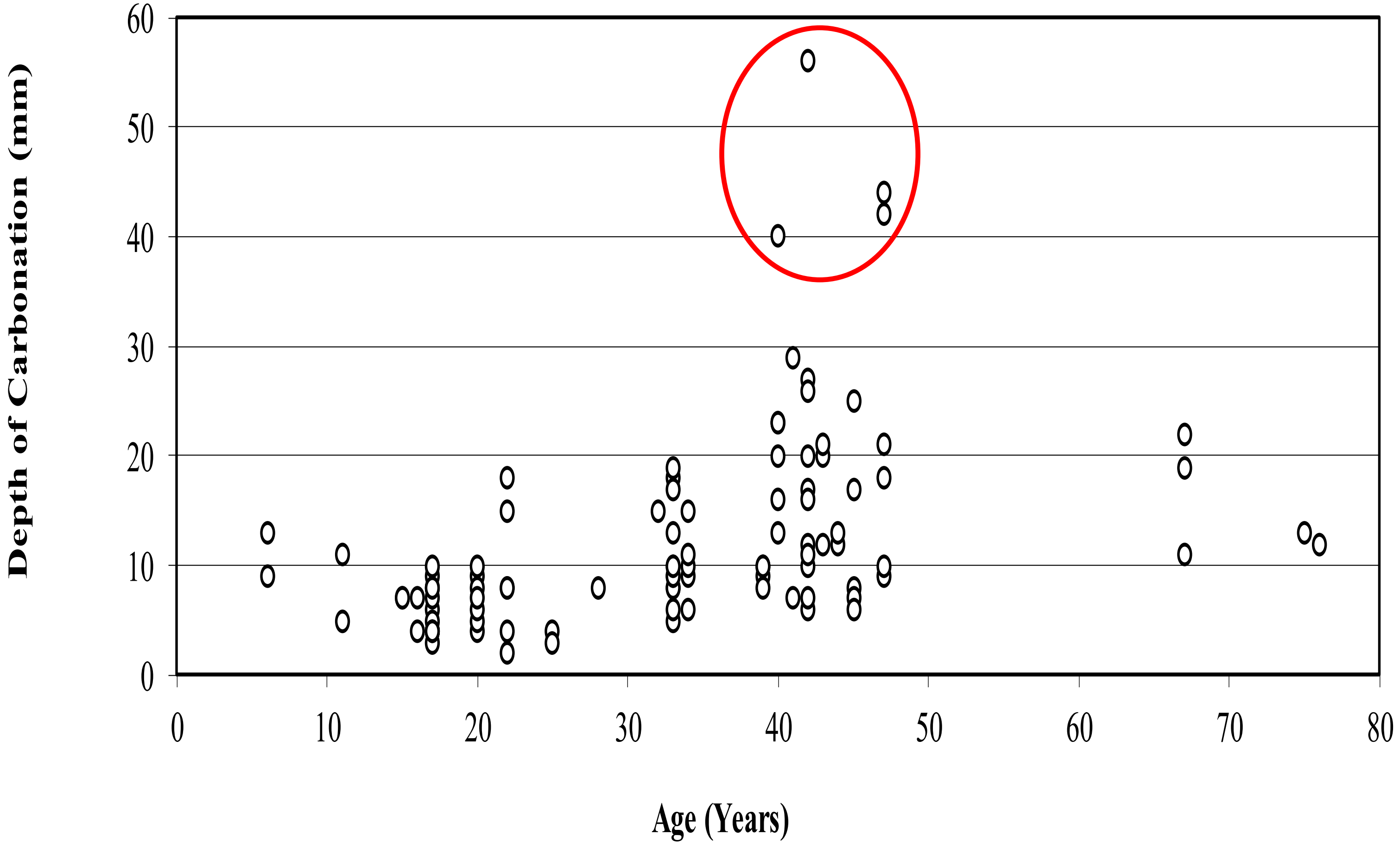
Source: PhD Thesis, E Leo, UCT 2022.

Clinker content:

LC3-45: 45%
LC3-55: 55%
LC3_65: 65%

LONG-TERM CARBONATION DATA, REAL STRUCTURES

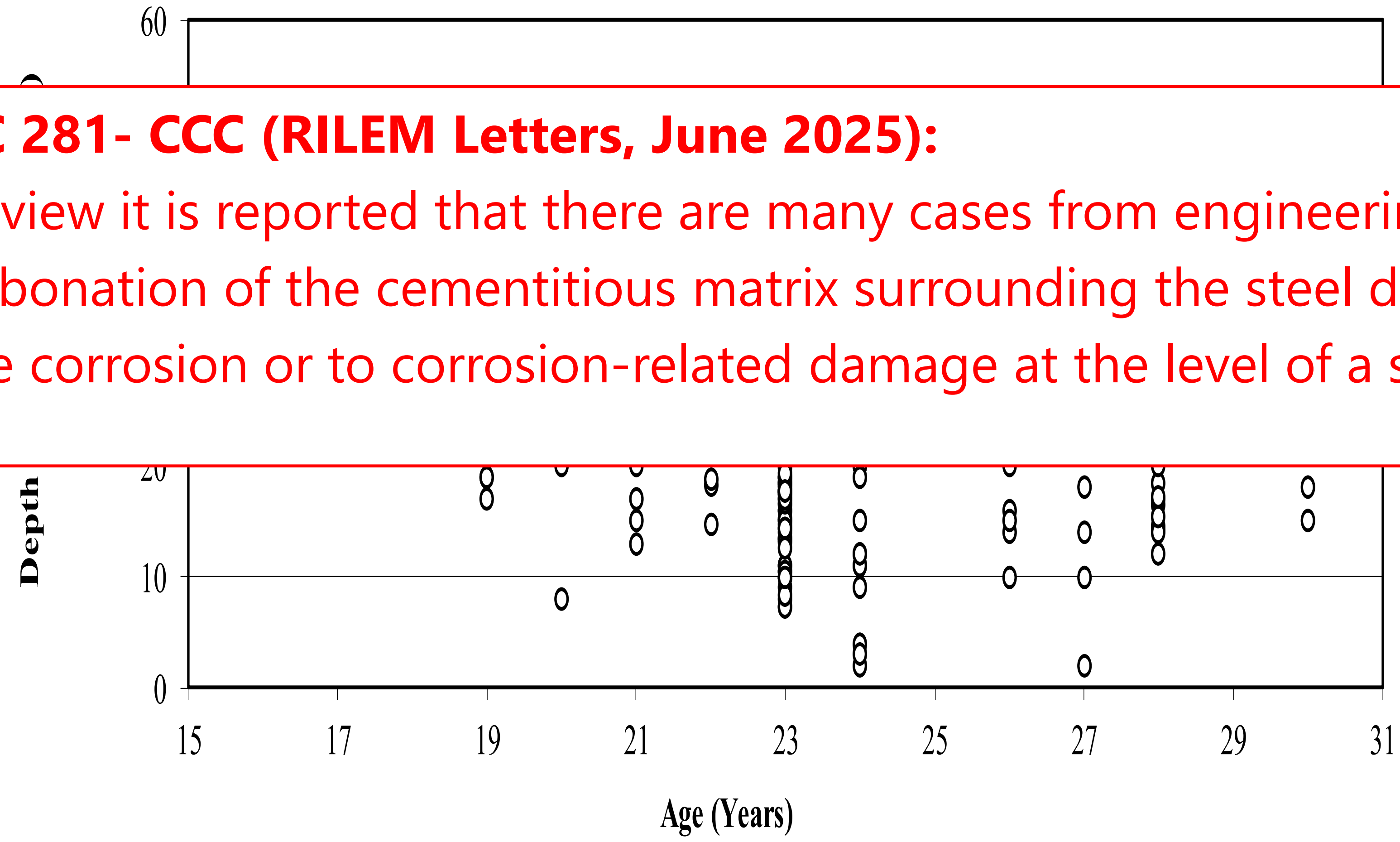
Overview of carbonation data a) Cape Peninsula, unsheltered. Concrete strength grades: 20, 30 and 40. Plain PC



Source: MSc Diss., W Yam, UCT, 2006

LONG-TERM CARBONATION DATA, REAL STRUCTURES

Overview of carbonation data b) Johannesburg, unsheltered.
Concrete strength grades: 30 and 35. Plain PC



RILEM TC 281- CCC (RILEM Letters, June 2025):

"In the review it is reported that there are many cases from engineering practice where carbonation of the cementitious matrix surrounding the steel did not lead to noticeable corrosion or to corrosion-related damage at the level of a structure."

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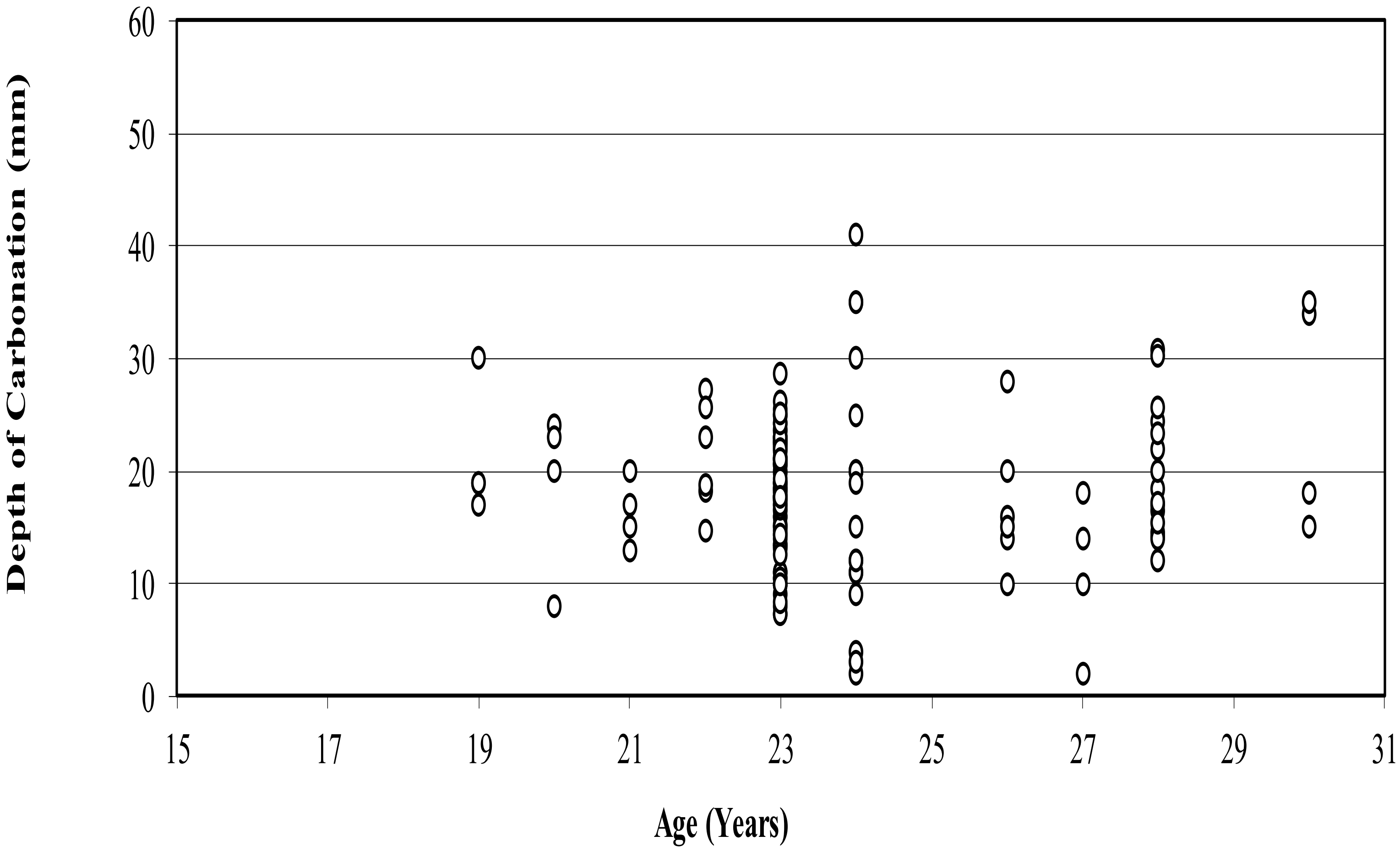


Source: MSc Diss., W Yam, UCT 2006

STANDARDS AND POLICY TO FACILITATE ADOPTION OF LOW-CARBON BINDERS

Engineers work to codes of practice, specifications etc.

Prescriptive vs performance-based specifications

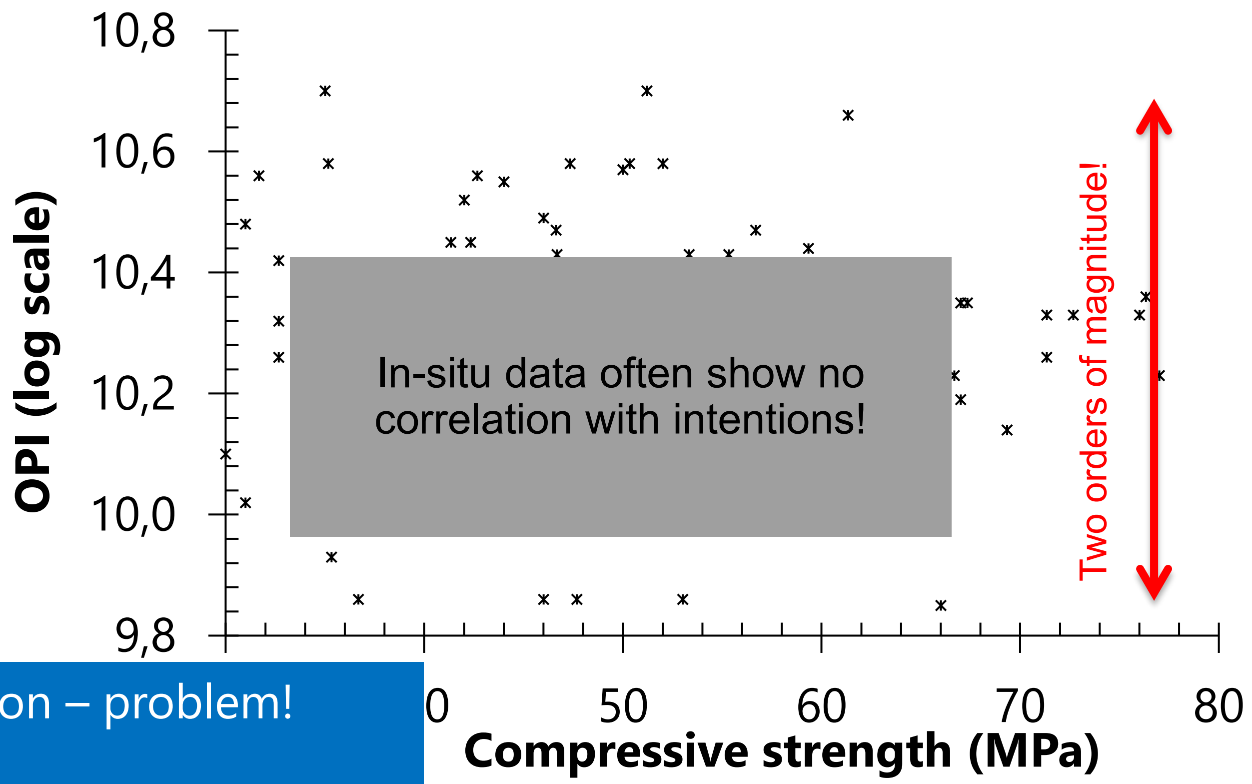
P2P INITIATIVE

- Importance of standards and codes – not something researchers like to do! If appropriate 'standards' are absent, uptake will be limited and sketchy.
- Need to move from prescriptive specs to performance specs – only way to handle rapid new developments!
- Specifications can be:
  - Materials specifications
  - Mix Design specifications
  - Construction specifications
- Prescriptive vs Performance Specs – see next slides

CONCRETE SPECIFICATIONS

Current Prescriptive approaches

- Deterministic, single-value answers
- No possibility for rational design
- Disadvantages are well-documented
- Strength still regarded as main 'durability-related' parameter; inadequate proxy



l and compressive strength (Nganga et al., 2012)

Research has run well ahead of practical implementation – problem!

Move to 'performance-based' specifications is gathering momentum – ref. NRMCA P2P; CSA A23.1; SA DI approach; Spanish and Swedish approaches, etc.

CONCRETE SPECIFICATIONS

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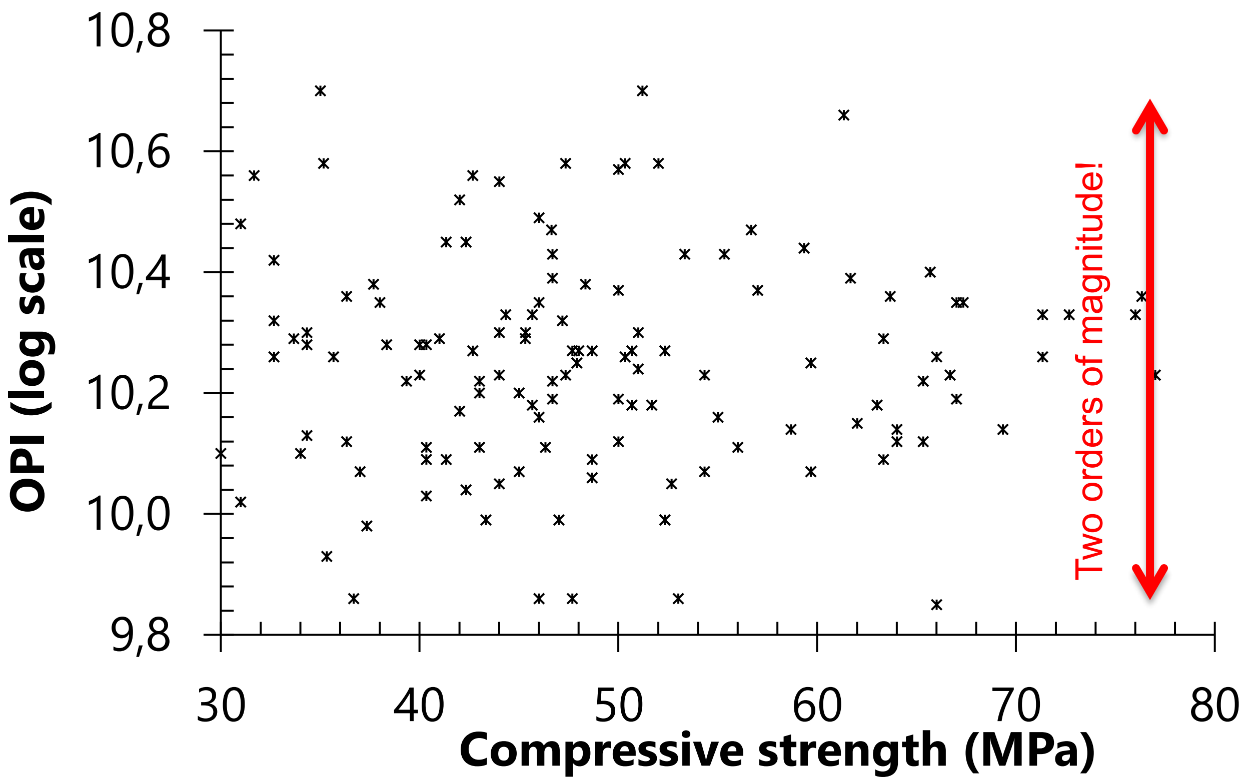


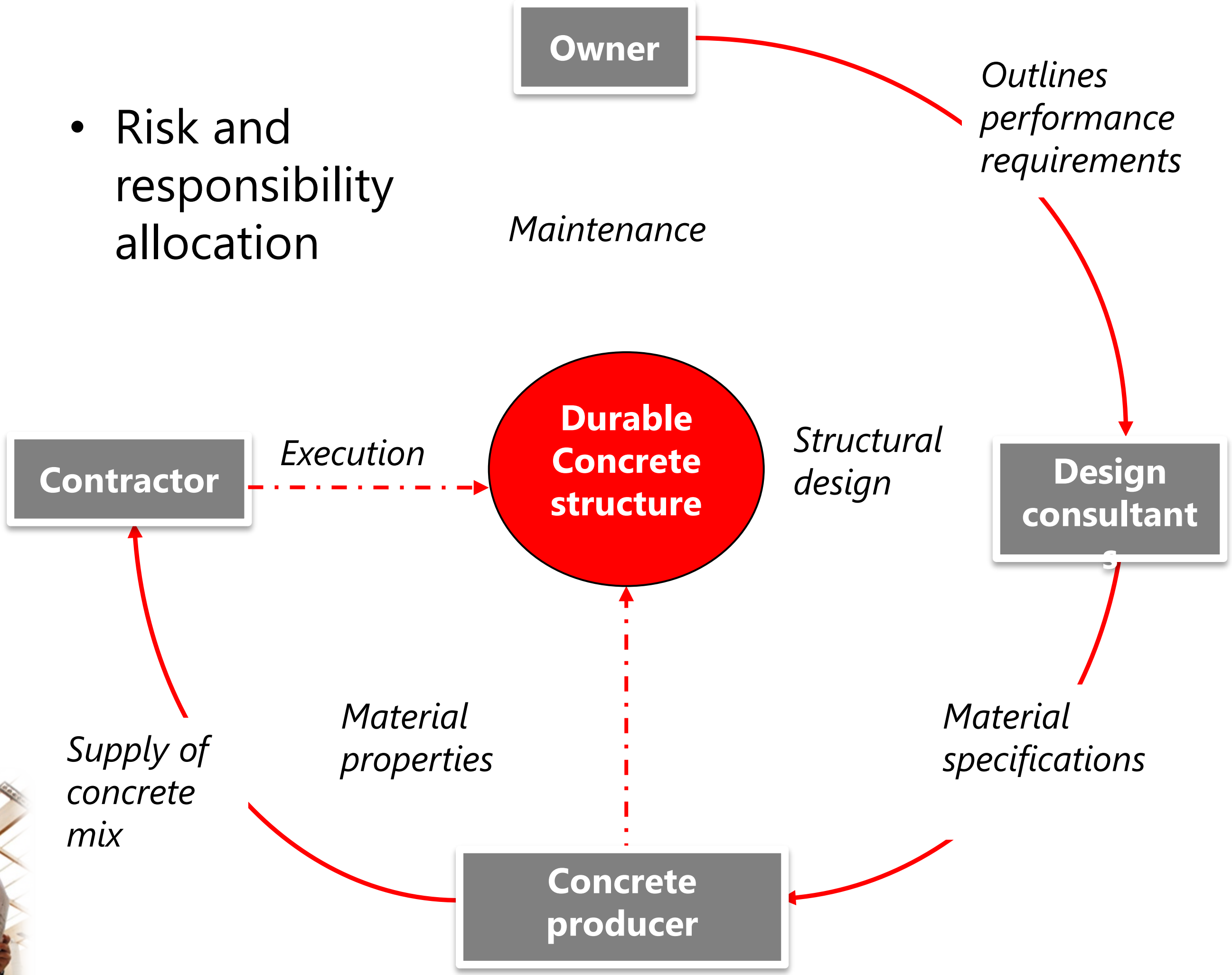
Comparison of OPI and compressive strength (Nganga et al., 2012)

CONCRETE SPECIFICATIONS

Performance-based approach

- Quantification of environmental loads and dominant deterioration mechanism(s)
- Performance criteria for the structure, e.g. definition of end-of-service life
- Prediction models for rate of deterioration
- Means of considering variability e.g. probabilistic, partial factors
- Appropriate specifications
and QA systems to verify compliance with required performance

- Risk and responsibility allocation



STANDARDS AND POLICY TO FACILITATE ADOPTION OF LOW-CARBON BINDERS

In addition to codes of practice, specifications, policy and regulations are also important.

In the future, expect policies, standards etc. to require a ‘sustainability’ metric, e.g. max. CO_{2e}.


BS EN 206:2013

BSI Standards Publication

Concrete — Specification, performance, production and conformity

Policy and standards needed at a broad (national, regional, international) level to drive changes; incentives need to be provided.

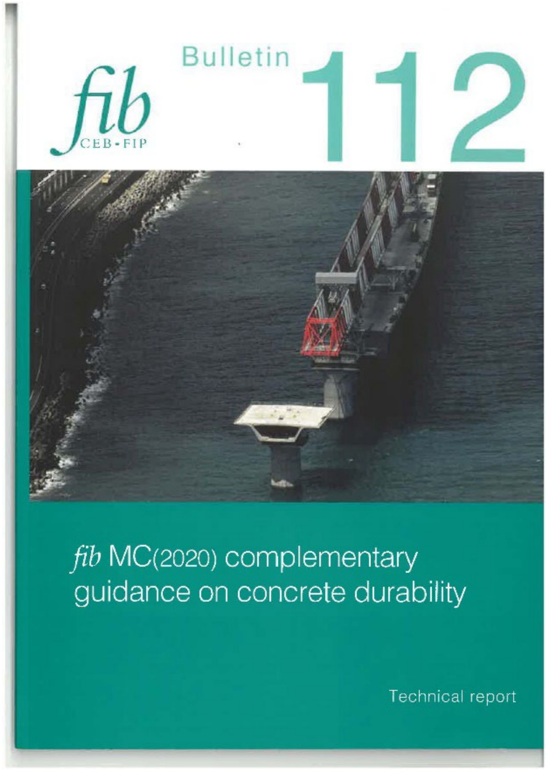
Hooton stresses:

- Lack of knowledge of performance specifications, including performance parameters and tests.
- Lack of appropriate specifications.
- Importance of defining roles and responsibilities in performance specs (owner, designer, contractor etc.). CSA A23.1 lays this out helpfully.

Need for ‘demonstration’ projects, i.e. live projects that show the efficacy of the applications in practice.

STANDARDS AND POLICY TO FACILITATE ADOPTION OF LOW-CARBON BINDERS

Progress???



भारतीय मानक
IS 18189 : 2023

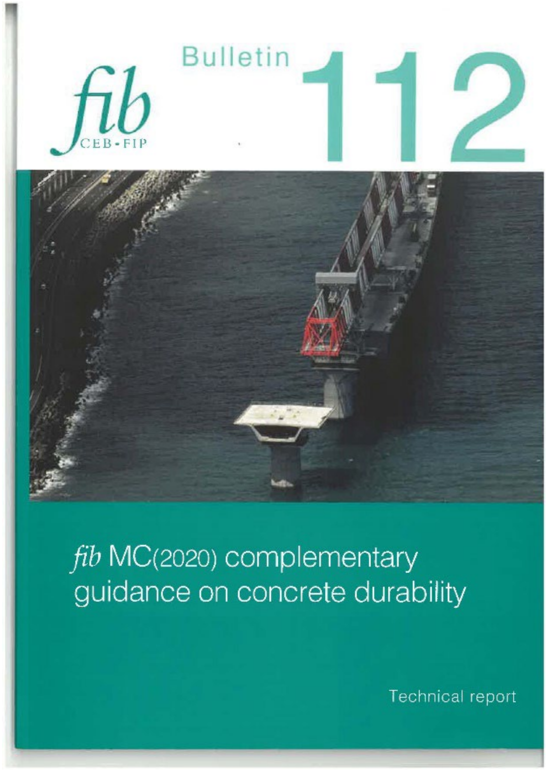
Indian Standard

पोर्टलैंड निस्तापित मृत्तिका चूना पत्थर सीमेंट — विशिष्टि

Portland Calcined Clay Limestone Cement — Specification

STANDARDS AND POLICY TO FACILITATE ADOPTION OF LOW-CARBON BINDERS

Progress???



- Current EN206 does not include explicit performance parameters / tests
- fib MC 2020 'toys' with these aspects
- Performance-based specifications do exist: e.g. CSA A23.1 (Mats & Constr), COTO (SA); PerfDub (France); GB/T50476 (China); Swiss SIA 262
- "Portland Calcined Clay Limestone Cement — Specification. IS (LC3)"; IS 18189 : 2023.
- ASTM C595: Std. Spec. for Blended Hydraulic Cements

CONCLUDING REMARKS

- Low carbon cements/concretes: used successfully for decades, e.g. high replacement level slag and FA cements.

  Imperative in order to embrace a sustainability paradigm.
- Newer low carbon cements: still untested in many instances –

FULTON:

SCRIVENER:

"Making cement is simple.

Making cement simple is very difficult!"

with associated challenges for low carbon systems

these cements.

- A comprehensive suite of performance specifications is needed to drive use forward. Ditto re policies and regulations.
- In many cases, 'durability' issues such as carbonation can be mitigated by suitable structural design and mix selection.

CONCLUDING REMARKS

- Low carbon cements/concretes: used successfully for decades, e.g. high replacement level slag and FA cements.

  Imperative in order to embrace a sustainability paradigm.
- Newer low carbon cements: still untested in many instances –

FULTON:

"Making good quality concrete is not difficult.

Making good quality concrete consistently is very difficult!"

- with associated challenges for low carbon systems

these cements.

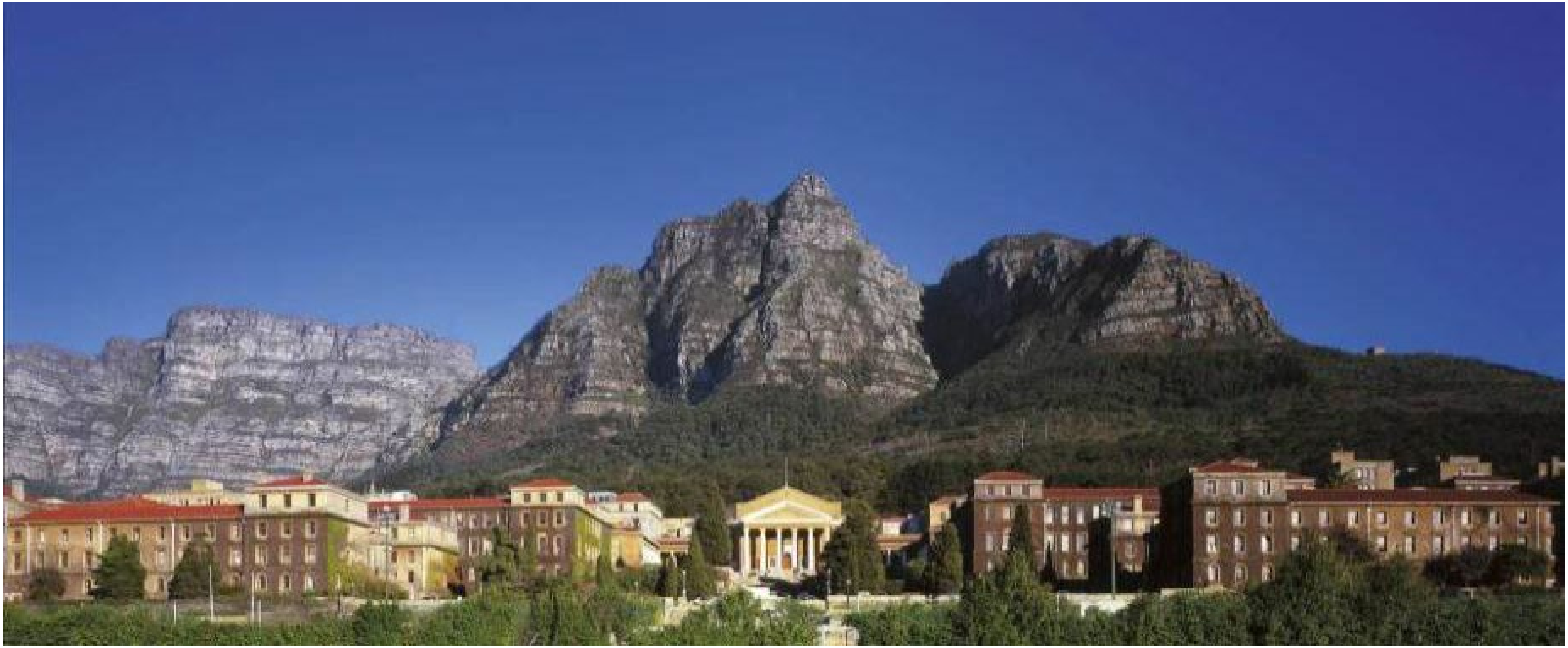
- A comprehensive suite of performance specifications is needed to drive use forward. Ditto re policies and regulations.
- In many cases, 'durability' issues such as carbonation can be mitigated by suitable structural design and mix selection.

CONCLUDING REMARKS

- Low carbon cements/concretes: used successfully for decades, e.g. high replacement level slag and FA cements.

  Imperative in order to embrace a sustainability paradigm.
- Newer low carbon cements: still untested in many instances – need proper field trials and longer-term verification, also in aggressive environments.
- Service life models for these newer materials are useful, but unlikely to be any more accurate than the existing models.
- Fundamental research still needed, including on production of these cements.
- A comprehensive suite of performance specifications is needed to drive use forward. Ditto re policies and regulations.
- In many cases, 'durability' issues such as carbonation can be mitigated by suitable structural design and mix selection.

THANK YOU – ENKOSI – DANKIE



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