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ENGINEERING & THE BUILT ENVIRONMENT
Concrete Materials & Structural Integrity Research Unit
CoMSIRU

Concrete durability: prescriptive and performance approaches, and examples from South Africa

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Outline

- Introduction – nature of the durability problem
- Performance-based approach to durability design & specification
- South African Durability Index Approach – premises, development, and implementation
- Performance-based durability specifications and site quality control
- Example of Implementation
- Closure

Introduction

- Durability (or the lack of it!) an enduring problem world-wide
- Corrosion in RC is the most serious durability issue
  - Quality of cover concrete (chemical & physical properties) of prime importance
- This can best be addressed by moving to *performance specifications* – better assign risk & responsibility
- Key challenge is reliable and appropriate tests to characterise the cover layer
- This lecture will review these aspects with specific reference to the SA approach developed in the recent past

Introduction

- Concrete is functional, efficient, universally available

- Concrete – developmental material *‘par excellence’*
- Used in huge quantities
  - Built environment sector comprises c. 70% of global material flows
  - Concrete accounts for c. 30% of materials usage in this sector

- Sustainability – concrete vs. others (Scrivener, 2014)

	Concrete	Fired clay bricks	Steel
Embodied energy (MJ/kg)	~ 0.95	~ 3.00	~ 35
CO_2 emissions (kg $CO_{2,\,eq}$/kg)	~ 0.13	~ 0.22	~ 2.80

Introduction

- However: problems with premature deterioration
  - ✓ Impact on economic growth, natural & non-renewable resources, safety
  - ✓ Economic losses - substantial

- Key questions
  - ✓ How do we address concrete deterioration – engineers, designers, owners?
  - ✓ What are the approaches to ensure durability in concrete construction, particularly in aggressive environments?
  - ✓ Is it possible to attach a notional 'design life' to a concrete structure?
  - ✓ What does 'Service Life Prediction' mean?

Performance-based approach –
to durability design & specification

- Rational ('engineering') approach to durability design and specification
- Provides integrated approach – the governing parameters should be used in design formulation, deterioration models and specification values
- Considers deterioration mechanisms
- Must be verification of performance properties that influence durability e.g. penetrability

Aspects considered in performance approach:-

- Quantification of environmental loads and dominant deterioration mechanism(s)
- Performance criteria for structure e.g. 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.

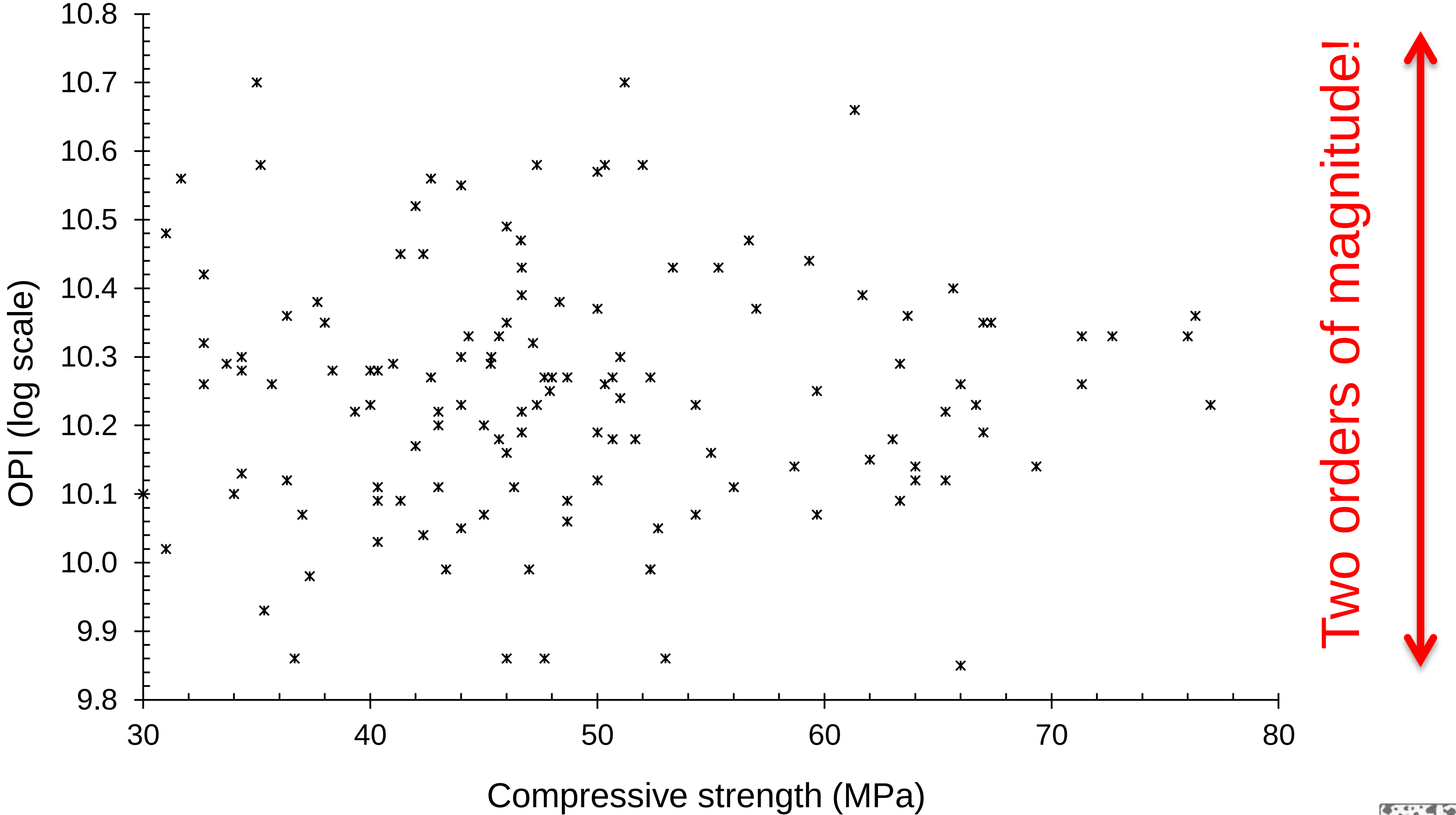
Construction specifications

Two main types of (durability) specifications:

1) Prescriptive – features:
   - Sets certain limiting values – mix materials & proportions
   - Sometimes prescribes construction processes, e.g. curing
   - Works on a 'deemed-to-satisfy' approach

- Main disadvantages: does not permit or 'guarantee'
  - In-situ verification of specified requirements
  - Quality of construction
  - Prediction for <u>service life requirements</u>
  - Economic analysis or maintenance budgeting
  - Innovation

- Example of drawback of prescriptive specifications:
  In-situ data often shows no correlation with intentions!



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

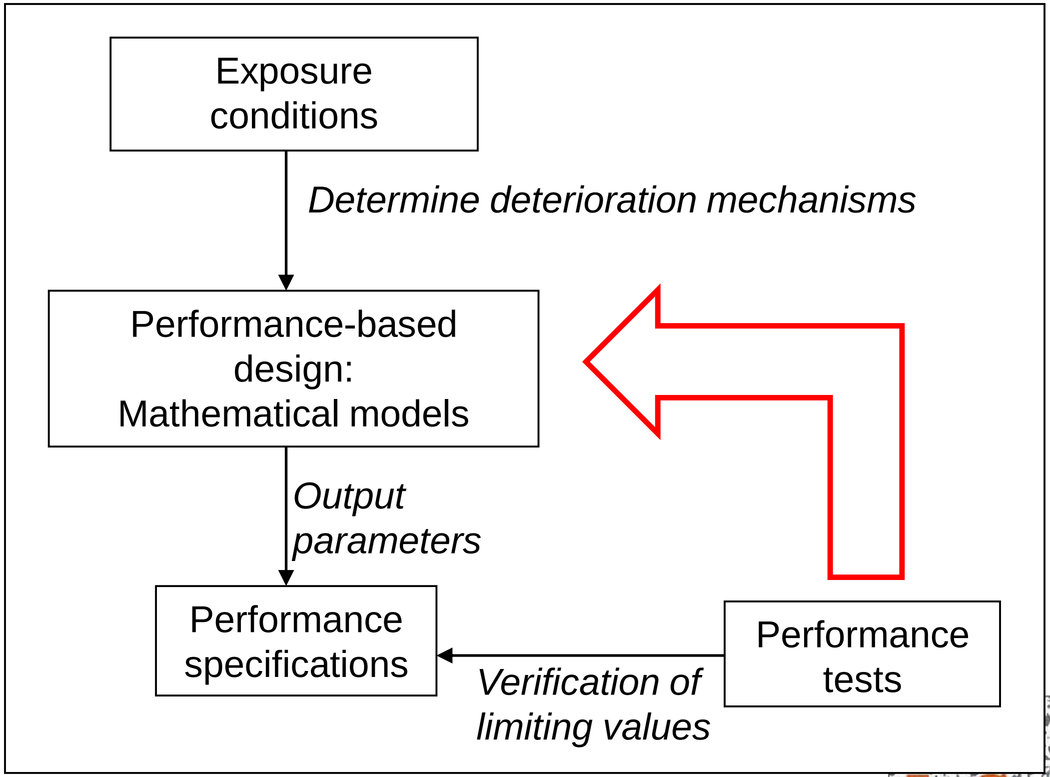
2) Performance – *'durability is a material performance concept for a structure'*

Features:

- Measurable performance criteria , specification of performance limits
- Robust, industry-accepted test methods

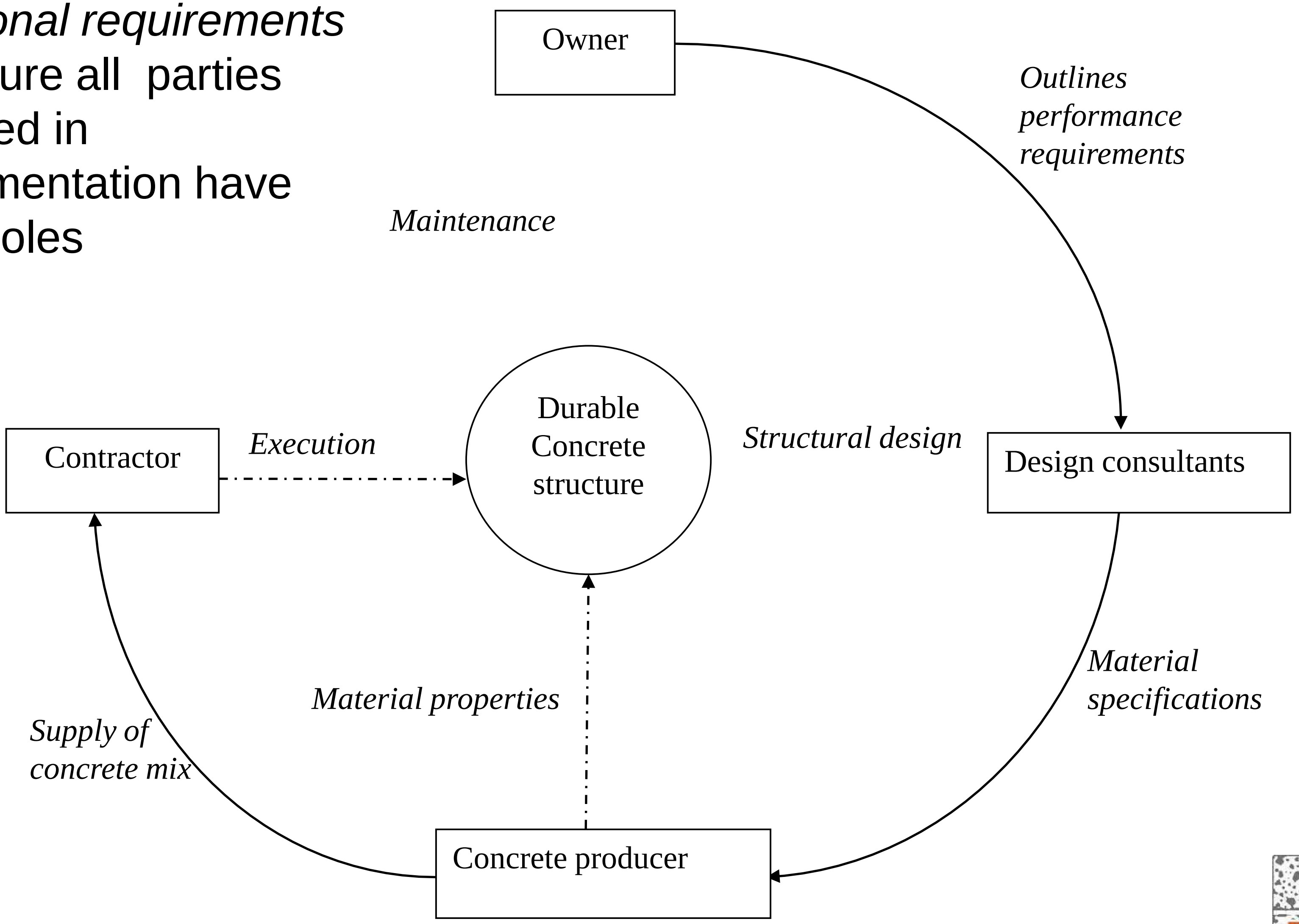
- Performance Limits:
  - To judge acceptable performance
  - Derived from SLMs, judgment, experience

- Main advantages lie in:
  - Integrated performance approach



(Somerville, 1997)

Requires definition of *functional requirements* to ensure all parties involved in implementation have clear roles



Performance testing

- Reliable test methods needed for
  - Mix pre-qualification prior to construction (material ‘potential’)
  - QC during construction – ‘as delivered’ concrete, and ‘as built’ structure !

- Various performance-based test methods developed in different parts of the world

  [RILEM TC – PSC; RILEM TC-NEC]

Durability indicators or indexes

- Physical, chemical, or electro-chemical parameters that characterise concrete *at an engineering level*
    - Easily interpreted in engineering context
    - Easily & reliably measured – gives confidence to engineers
    - Sensitive to processing, environmental factors
    - Powerful means to characterise concrete – potential durability
    - Typical parameters include;
        - Conventional – permeability, conductivity, etc.
        - Indirect – porosity index, chemical properties
- Examples
    - Resistivity – chlorides, penetrability, etc.
    - RCPT / RCM / CCI - chloride resistance
    - Oxygen permeability index – carbonation resistance
    - CH residual

South African Durability Index Approach – premises, development, and implementation

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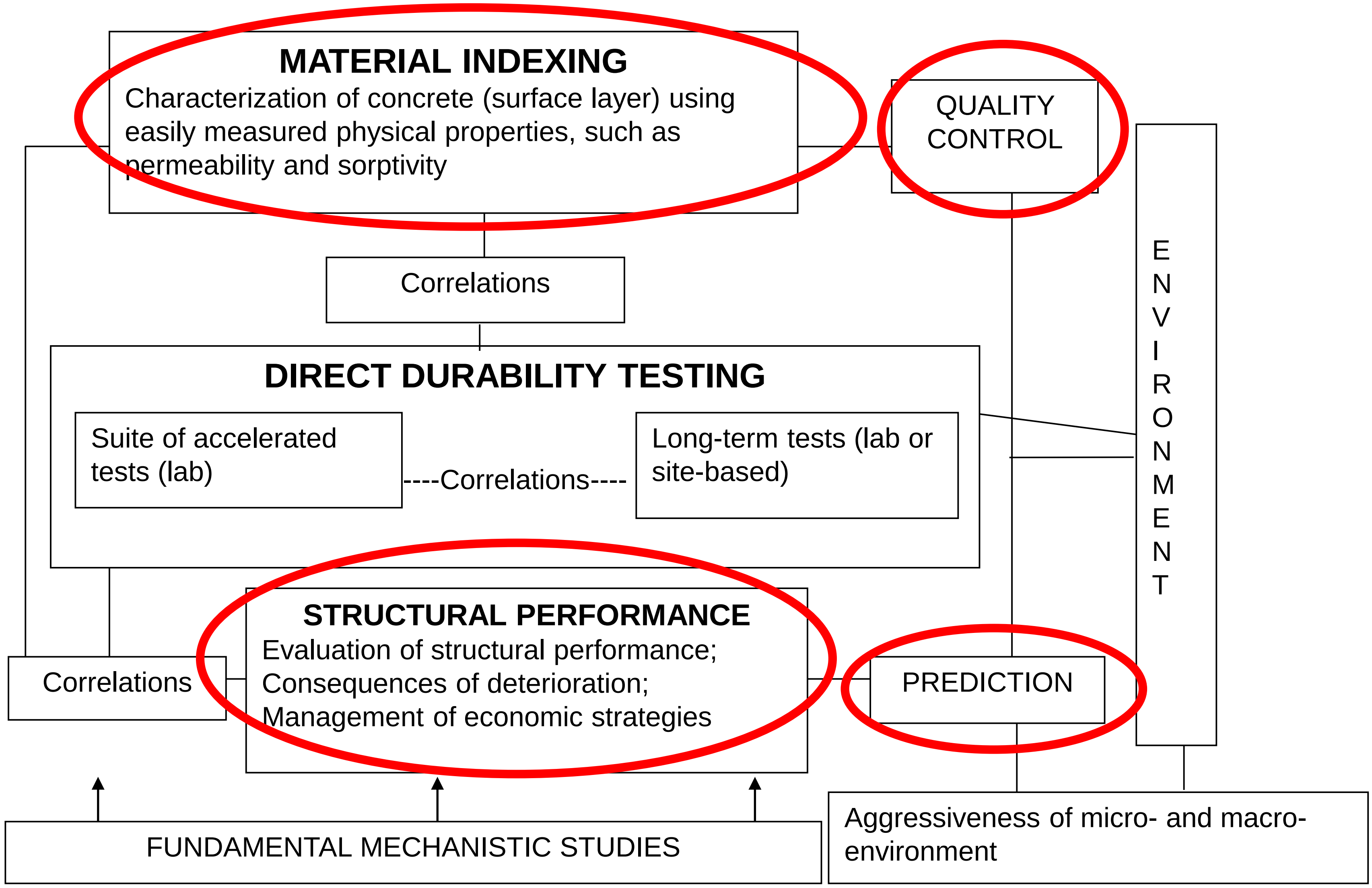
Overall objectives of our durability work

To provide a framework for:

- the designer to establish the required level of performance
- the material producer to produce concrete of an acceptable 'potential durability'
- the constructor to achieve an as-built structure of the desired quality, implying:
  - the owner can be assured that the desired quality is actually achieved!

The above is premised upon the Durability Index approach

South African Framework – “Durability Index Approach”



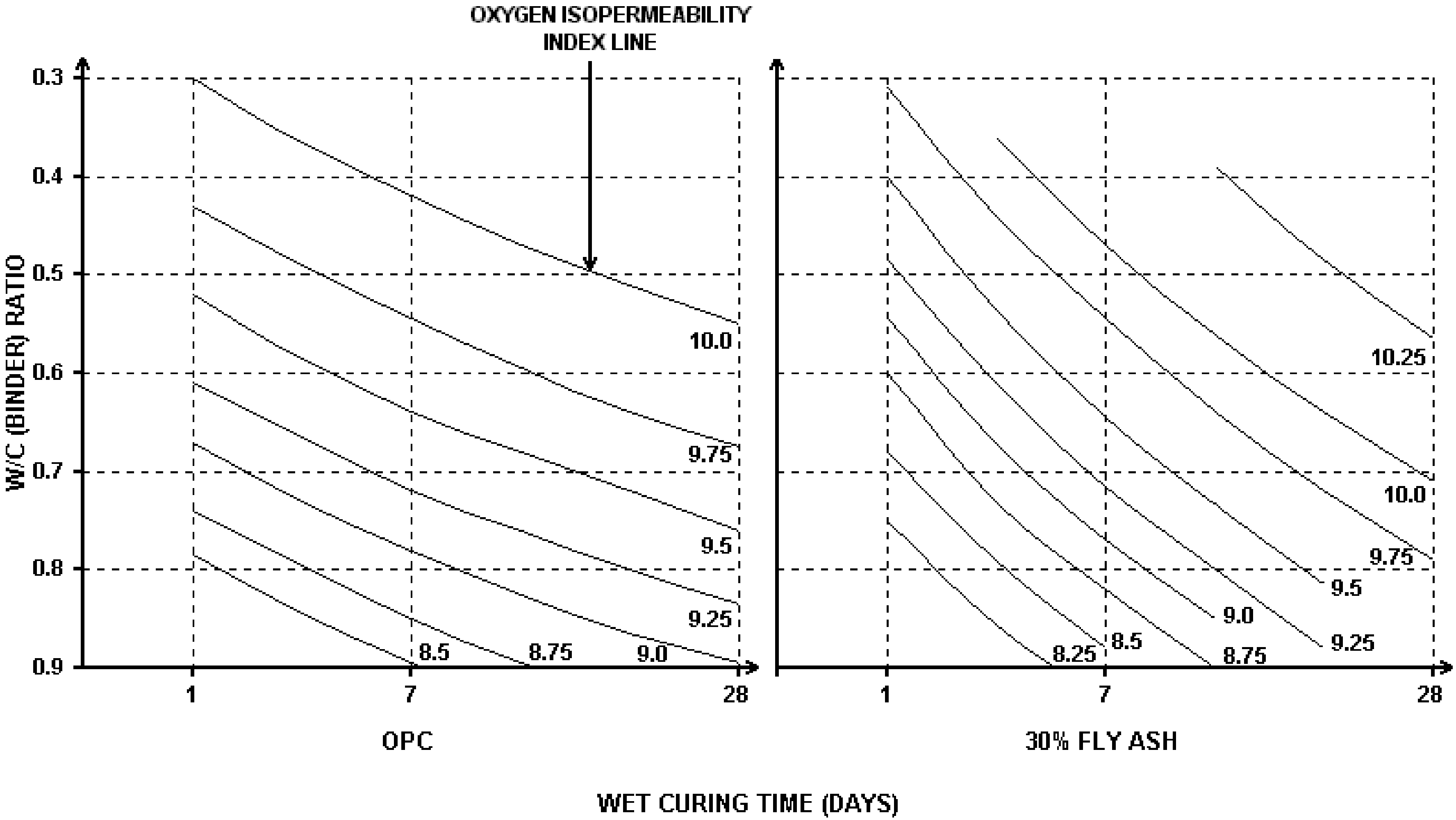
DI approach - Premises

- The durability of RC structures depends on the ability of the cover to protect the reinforcing steel
  - i.e. the quality and thickness of the cover
- Improved durability will best be assured if relevant durability parameters reflecting the quality of the cover layer can be measured – so-called 'Durability Indexes'.
- A Durability Index (DI) is thus
  - a quantifiable engineering parameter that characterises concrete durability (quality)
  - sensitive to material, processing, and environmental factors, and
  - based on measurement of transport properties of the cover layer - lab or in-situ concrete
- DIs should be linked with transport mechanisms that relate to deterioration.

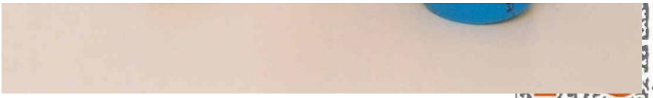
Review of:

- DI Tests
- Service Life Models - brief

Oxygen Permeability Index (OPI) Test

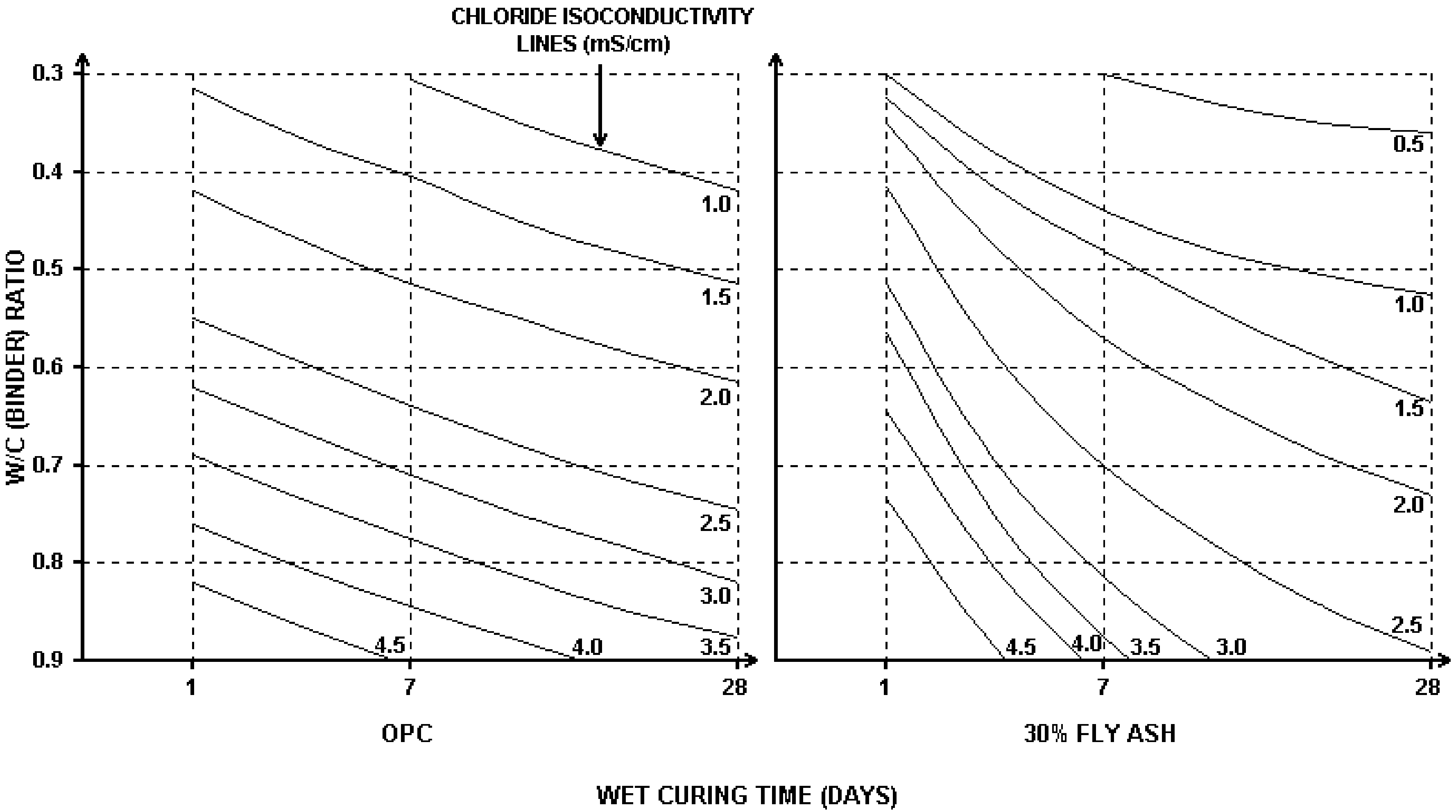


pre-conditioned



Test methods

Chloride resistance



Service life models

- Initiation models:
  - One SLM for carbonation resistance, using 28-day OPI as a parameter
  - One SLM for chloride resistance, using 28-day CCI as input to a Fickian model
- Account for material type and environment
- Integrated approach: DI parameters are used
  - In design, via the SLMs
  - In specification – min. required values
  - For quality control on site – checks on as-built values

Criteria for establishing a performance approach

1. A Robust Quality Control Test
   - Routine, easily-carried out, reliable measure of resistance (e.g. to chloride ingress)
2. A Service Life Model
   - Relates performance to the quality control test (e.g. in terms of limiting material parameters)
3. A means to account for differences (i.e. ‘Margins’) between ‘Material Potential’ and ‘As-Built’ values
   - In order to differentiate between areas of responsibility (e.g. material supplier & constructor)

Examples of Implementation:

Performance-based durability design

Design methodology

- Related to Service Life Prediction Models
- Concerned with carbonation- and chloride-induced corrosion (initiation)
- Requirements:
  - Notional design life of structure
  - Exposure Class(es) (EN 206)
  - Concrete quality represented by durability index parameters
  - Cover 'quantity, i.e. thickness

Items in red are the Owner's decisions

Design methodology can be applied to two conditions:

1. ‘Standard Service Life Conditions’ approach

   (based on ‘standard’ sets of design conditions)

   Cover selected for

   - Carbonation: 30 mm
   - Seawater: 50 mm

   Cover needs to be checked by covermeter surveys post-construction

2. Rigorous approach – only briefly touched on here

Design life – EN1990

Design Life Category	Indicative Design Working Life	Examples of Structures
1	10 years	Temporary
2	10 to 25 years	Replaceable Structural Parts
3	15 to 30 years	Agricultural and Similar Structures
4	50 years	Buildings and Other Common Structures
5	100 years	Monumental Building Structures, & Civil Engineering Structures

Carbonation Environmental Categories
(after EN 206)

Designation	Description
XC1	Permanently Wet or Permanently Dry
XC2	Wet, Rarely Dry
XC3	Moderate Humidity (60-80 %)
XC4	Cyclic Wet and Dry

Categories refer to the moisture state at the level of the steel.

Carbonation – ‘Standard conditions’

For structures in environment XC3/4,
an OPI requirement is necessary

	Common Structures	Monumental Structures (1)	Monumental Structures (2)
Service Life	50 years	100 years	100 years
Minimum Cover	30 mm	30 mm	40 mm
Minimum OPI	9.70	9.90	9.70

Min. OPI is value that must be achieved in as-built structure at 28 d

Seawater Environmental Categories
(after EN 206)

Designation	Description
XS1	Exposed to airborne salt, < 5 km from sea east <15 km from sea west of Cape Agulhas
XS2a	Permanently Submerged
XS2b	XS2a + exposed to abrasion
XS3a	Tidal, splash and wetted spray zones
XS3b	XS3a + exposed to abrasion

Seawater Environment

‘Standard conditions’

- A chloride conductivity value is used
- Minimum cover of 50 mm
- Common Structures – 50 year life
- Monumental Structures – 100 year life

Chloride Ingress – Monumental Structures

Max. Chlor. Cond. Values (mS/cm)

(100y life)

ENV Class	70:30 CEMI:FA	50:50 CEMI:GGBS	50:50 CEMI:GGCS	90:10 CEM I:CSF
XS1	2.50	2.80	3.50	0.80
XS2a	2.15	2.30	2.90	0.50
XS2b, XS3a	1.10	1.35	1.60	0.35
XS3b	0.90	1.05	1.30	0.25

Maximum w/b of 0.55

These are max. CC values that should not be exceeded in the as-built structure at 28 d

Rigorous Approach

Marine Struct. 50-y design life		Max. chloride conductivity (mS/cm) for various binder types		
Exposure class (based on EN 206)	**Cover (mm)**	**100% CEM I**	**30% fly ash**	**50% Corex slag**
XS3b: Tidal, splash and wetted spray zones, exposed to abrasion	40	0.45	0.75	1.05
	60	0.95	1.35	1.95
	80	1.30	1.80	2.60
XS0b: Airborne salt in an exposed near-shore marine location	40	1.00	1.85	2.50
	60	1.85	2.95	3.90
	80	2.50	3.75	4.80

Legend		
	(red)	Impractical mixes; concrete grade > 60 MPa
	(yellow-green)	Not recomm.: < 30 MPa, and/or w/b > 0.55
	(green)	Acceptable: Grades from 30 to 60 MPa

Note 'trade-off' between mat'l. quality and cover

Performance-based durability specifications and site quality control

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Material Potential vs. As-Built Construction Quality

Major consequences of the current prescriptive approach:

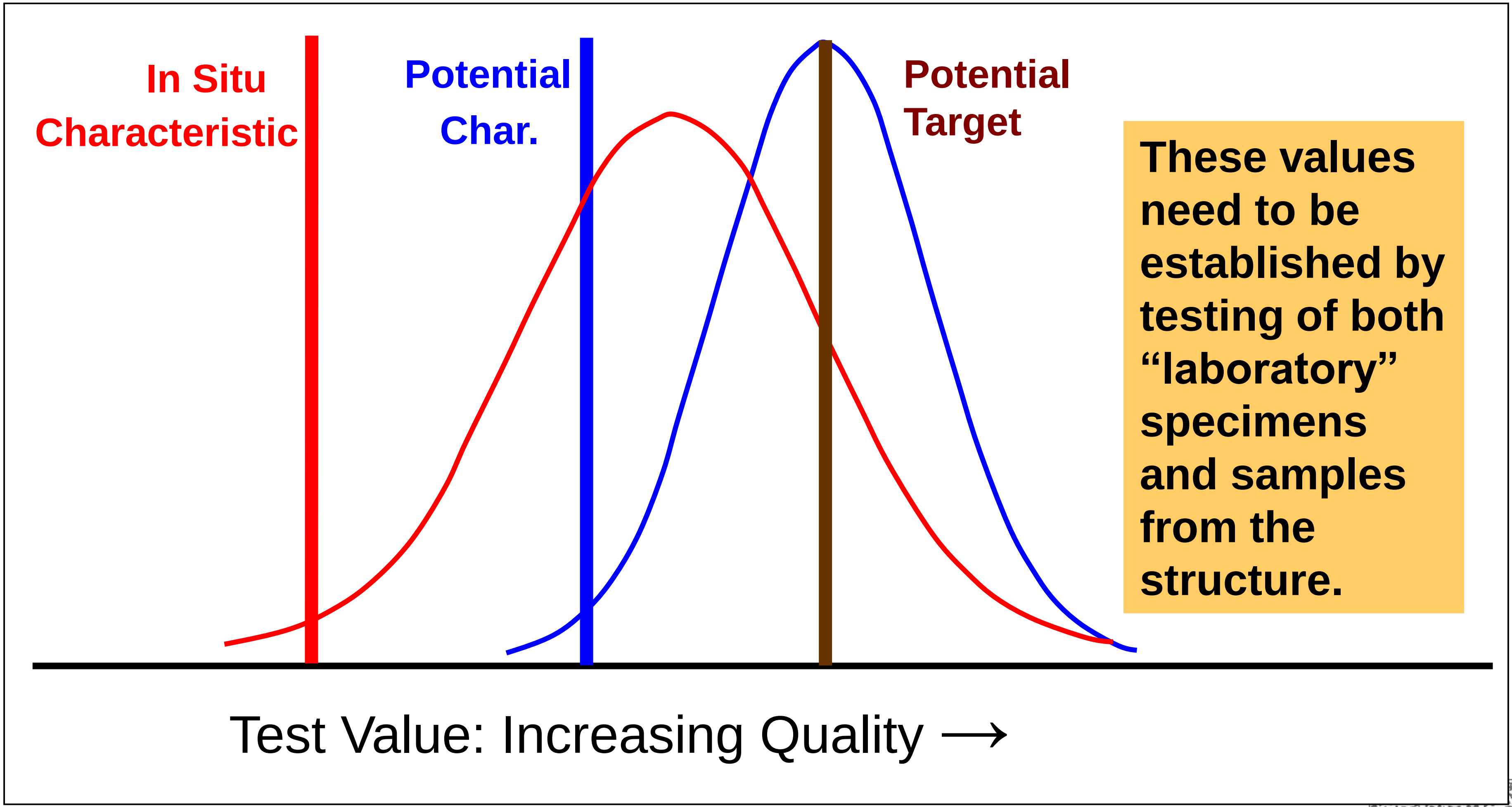
- ❑ it cannot assess <u>actual as-built quality</u> of the concrete
- ❑ it simplistically assumes as-built quality to be what is specified

Material Potential vs. As-Built Construction Quality

- Specifications are concerned with as-built quality BUT

  Production process cannot be ignored
- Two stages in addressing concrete of desired quality:
  - material production & supply
  - concrete placing and finishing
    - Deficiencies can arise in both stages
- Therefore, we need a two-level quality control process to distinguish between material potential & as-built quality

Material Potential vs As-Built Values



These values need to be established by testing of both "laboratory" specimens and samples from the structure.

Example of Implementation: GFIP (SANRAL)

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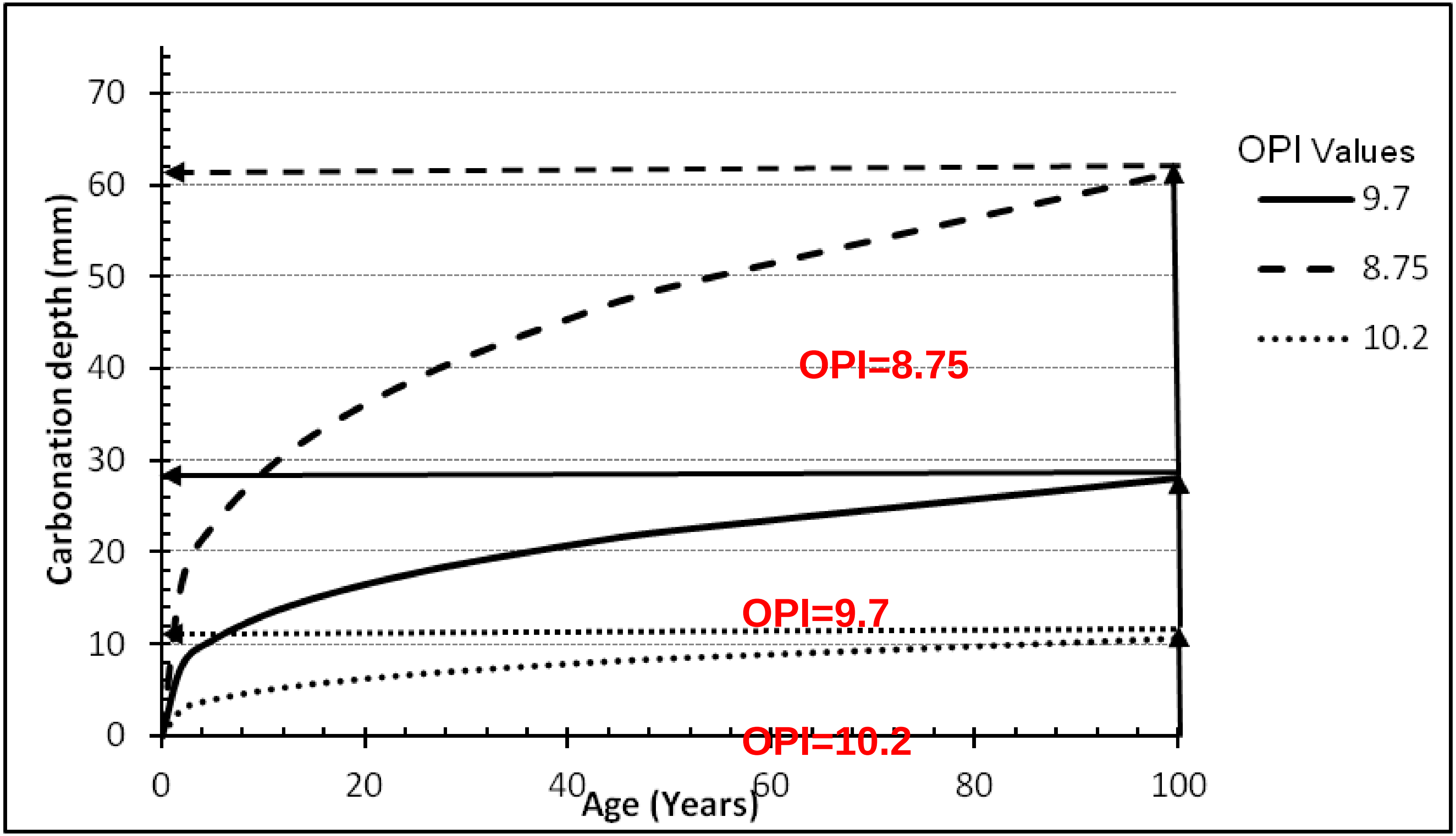
Example of Implementation: GFIP (SANRAL)



DI prediction model for inland exposure conditions, R.H. = 60%, OPI = 9.70, and 100% CEM I binder

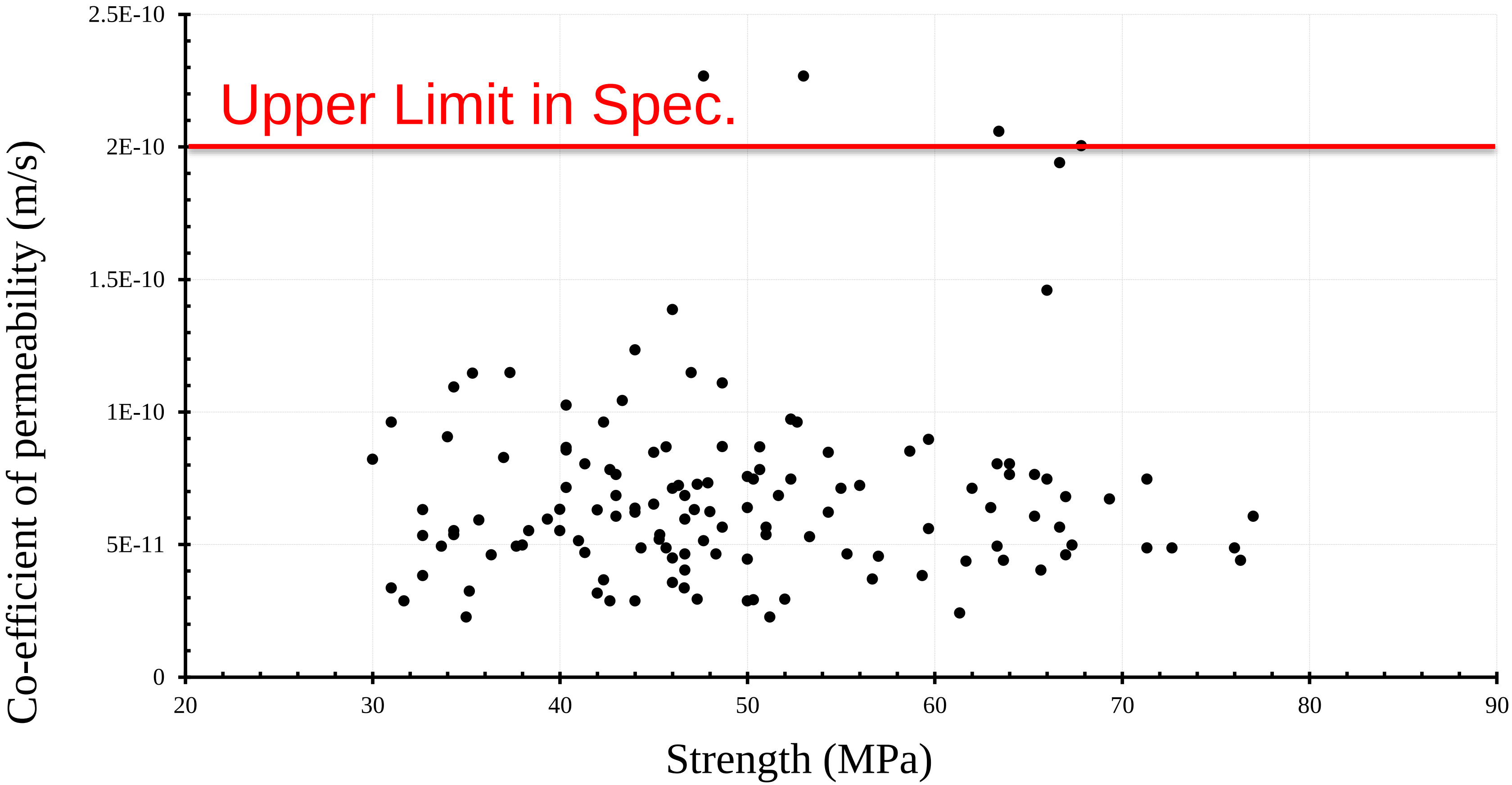
Example of Implementation: GFIP (SANRAL)

N'ganga (2012)

- Study to evaluate practicality of the DI performance-based approach, by considering:
  - Extent of variability in test results
  - Applicability of the test in laboratories
  - Perception of resident engineers on the approach

- Data obtained from:
  - GFIP work packages
  - Questionnaires sent out to resident engineers
  - Review of a laboratory audit report

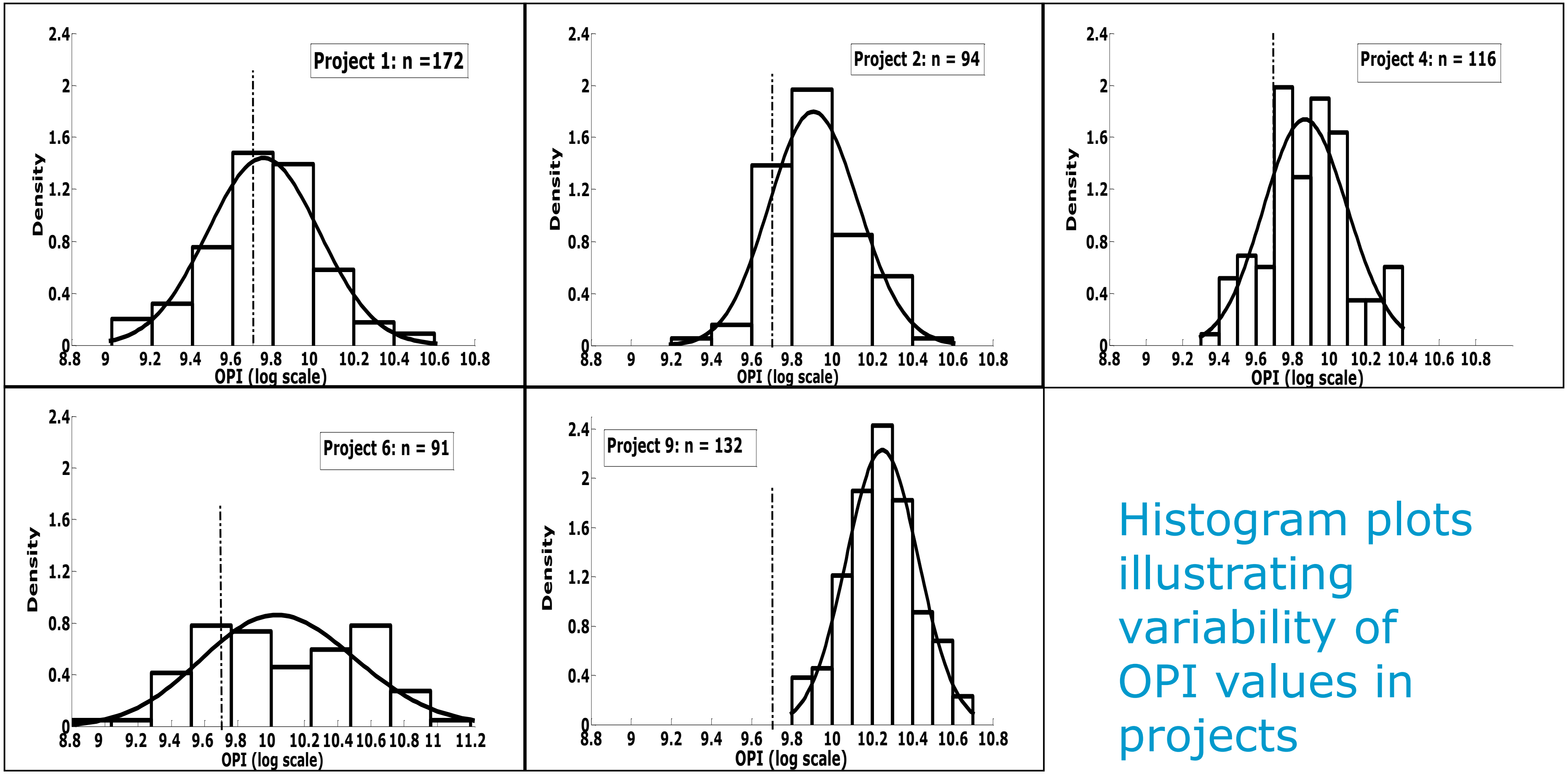
Example of Implementation: lack of correlation between 'durability' and compressive strength from GFIP – permeability vs. f_{cu}



Statistical summary (OPI):

Project ID	OPI (log scale) n	Mean	Max	Min	s	CoV (%)	Proportion of defectives %
1	172	9.75	10.41	9.07	0.28	2.84	**40.1**
2	94	9.91	10.42	9.37	0.22	2.24	**13.8**
4	116	9.87	10.40	9.39	0.23	2.33	**18.1**
6	91	10.06	11.10	8.83	0.46	4.60	**26.4**
9	**132**	**10.25**	**10.70**	**9.85**	**0.18**	**1.75**	**0**

- **Project 1, 2, 4, 6: in-situ samples; Project 9 - precast element samples.**



Histogram plots illustrating variability of OPI values in projects

Statistical summary:

- All mean OPI values comply with limit value of 9.70
- Nevertheless, large ‘proportion of defectives’ for certain as-built structures
- Variability (CoV) and proportion of defectives lowest for precast samples
    - Better control exercised in precast unit manufacture than for in-situ construction

Current limitations in application

- More work required on test/sample variability: between batch variability, and in-situ variability
- This will give more confidence in relationships between target and characteristic material value
- Very little information on magnitude of reduction in values between lab standard cured samples and in-situ achievements
- Need information on actual as-built values, to confirm validity of approach

Closure

- Presentation has described the background to performance-based specifications, and in particular, development of the Durability Index approach in SA, for improving quality of R. C. construction
- Approach relies on site-applicable DI tests and linked Service Life Models
- Performance-based Design and Specification methods flow from this approach
- Approach can be used to optimize balance between concrete quality and cover thickness
- Work is required to correlate DI values and actual as-built performance

Thank You धन्यवाद !

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