Performance-based durability design and specifications for concrete structures

Mark G. Alexander

Concrete Materials and Structural Integrity Research Unit
University of Cape Town

Presented at 54th CBC – Brazilian Conference on Concrete
Maceio, October 2012

Outline

- Introduction - nature of the problem
- Frameworks: Durability studies; Performance-based durability design & specification
- Premises of “Durability Index” (DI) approach
- Review of test methods and service life models
- Examples of implementation
- Current SA Code developments
- Closure

Introduction

- Durability of R.C. structures – a problem for owners/managers
- Corrosion resistance: relates to resistance of cover layer to external aggressive agents
- Thus: quality plus thickness of the cover needs to be quantified, measured, and specified
- Cover quality: should relate to measured transport properties, e.g. permeability, diffusion
- Present specifications
  - Prescriptive – generally ineffective for durability issues
  - New approaches must incorporate performance-based design and specification:
    - ✓ to encourage innovation
    - ✓ to improve quality of as-built structures


Examples of marine concrete deterioration – Cape Town

Frameworks for:

Performance-based durability design and specification

Prescriptive vs. performance-based approaches

- Prescriptive specifications – ‘recipe’ type, giving limits on mix parameters, etc.
  - Represent most current specifications
  - Restrictive and not able to accommodate modern developments
  - Ineffective in many cases when it comes to durability
- Performance-based specifications – rely on measured parameters from the actual structure which correspond to deterioration mechanisms
  - Linked with Service Life Models
  - Permit innovation and new approaches to achieving desired performance

Prescriptive vs. performance-based approaches

Major consequences of the 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

Aim - provide a framework

- for the designer/owner to establish the required level of performance…and
- within which
  - the material producer and constructor can produce a structure of desired quality
  - the owner can be assured that the quality desired is actually achieved

The ultimate objective is to produce a performance-based set of durability design and specification protocols

These need to be framed in a fully probabilistic approach, leading to measures of 'Reliability'

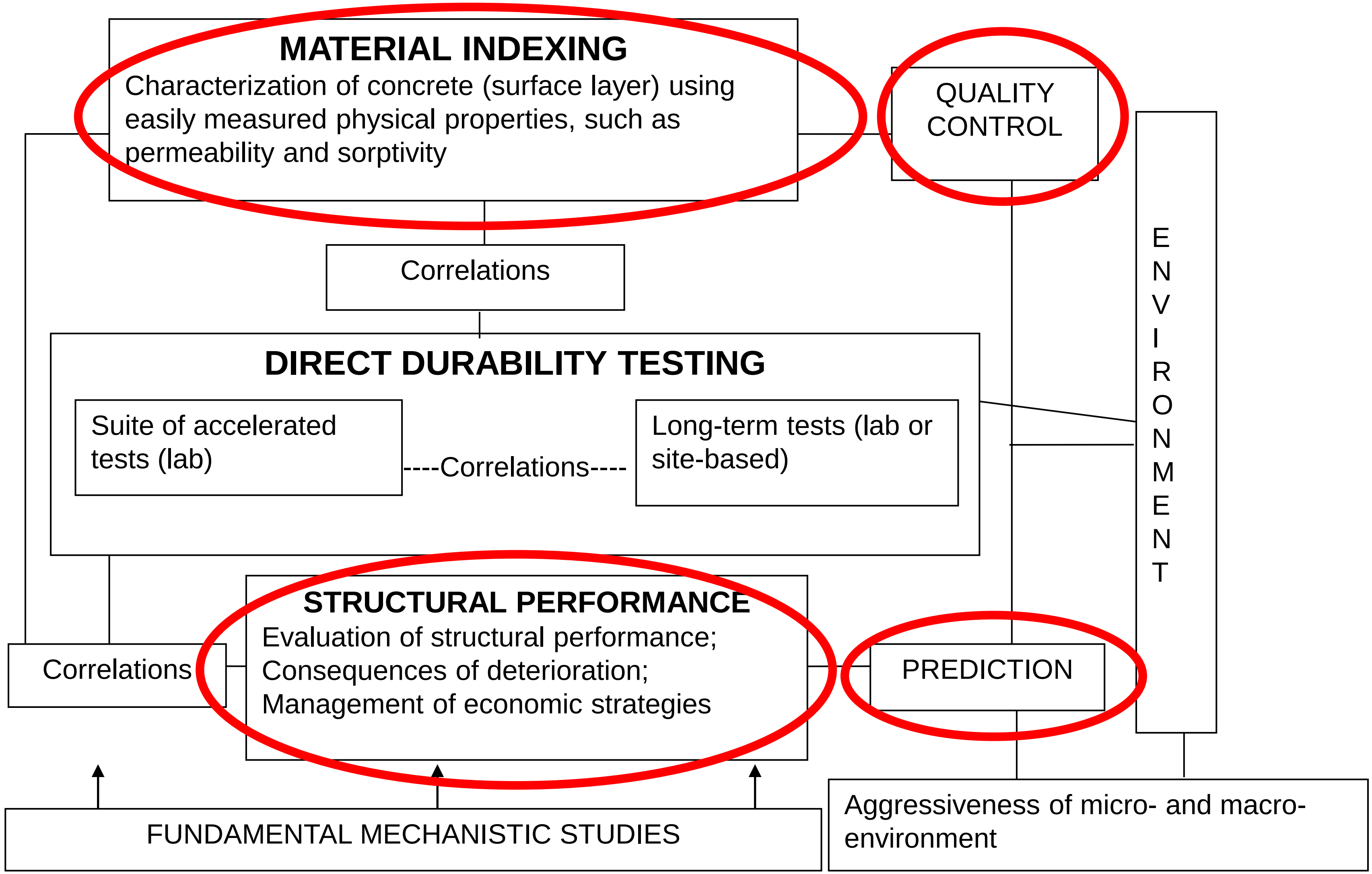
Framework for performance-based durability design & specification. Current SA Developments

STEPS FOR DEVELOPMENT (1 TO 4)	
Durability design	**Durability specification**
1. Define exposure classes related to the mechanism(s) of deterioration	
Adopt EN 206 exposure classification	
2. Derive a quantitative design methodology, incl. definition of end of design life	
Predictive service life (Initiation) models	Account for required design life of structure, for ‘no’ corrosion
3. Develop test methods that relate to the input parameters of the design method	
DI characterisation tests; input parameters to the service life models	Specs. require DI values to meet criteria in 2. above
4. Produce provisional conformity criteria and calibrate against traditional solutions	
Currently: ‘Deemed-to satisfy’ values; alt. rigorous approach	‘Deemed-to-satisfy’ values: both material supplier and constructor

Framework for Performance-based design & specification

STEPS FOR DEVELOPMENT (5 to 7)	
Durability design	**Durability specification**
5. Establish limitations of test applicability	
DI tests: moderate to high-grade concretes; not valid for very HSC, special concretes.	Specs. cover 'typical' normal construction
6. Ensure production control and acceptance testing	
Differentiate between quality 'as-supplied' (manufacturer's responsibility) & as-built (constructor's responsibility).	Two-level requirement :'as-supplied' vs. 'as-built' DI s. (Owner requires final 'as-built' values only)
7. Conduct full-scale trials and long-term monitoring to confirm conformity requirements	
Studies required to give confidence in use of the approach and to calibrate the test results for local materials. Introduce the approach incrementally, build up a database of DI values to inform later improvements.	

South African Framework – "Durability Index Approach"



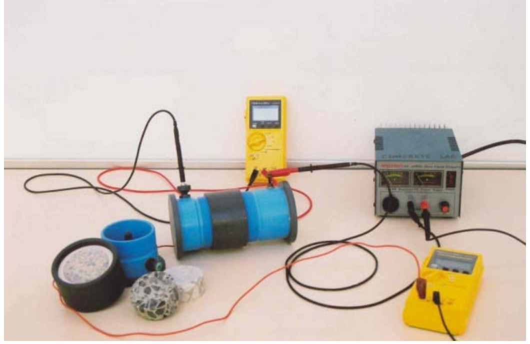
SA Durability index approach - Premises

- 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 concrete cover
- Improved durability can be assured if relevant durability parameters reflecting the quality of the cover layer can be measured
- In South Africa, we have developed such durability parameters and tests
  – so-called 'Durability Indexes'

SA Durability index approach - Premises

- A Durability Index (DI) is thus
  - a quantifiable engineering parameter that characterises concrete durability (quality)
  - sensitive to material, processing, and environmental factors
  - based on measurement of transport properties of **the cover layer - lab or in-situ concrete**
- DIs are linked with transport mechanisms that relate to deterioration
- DIs are also incorporated into Service Life Models that permit rational

  Durability Design



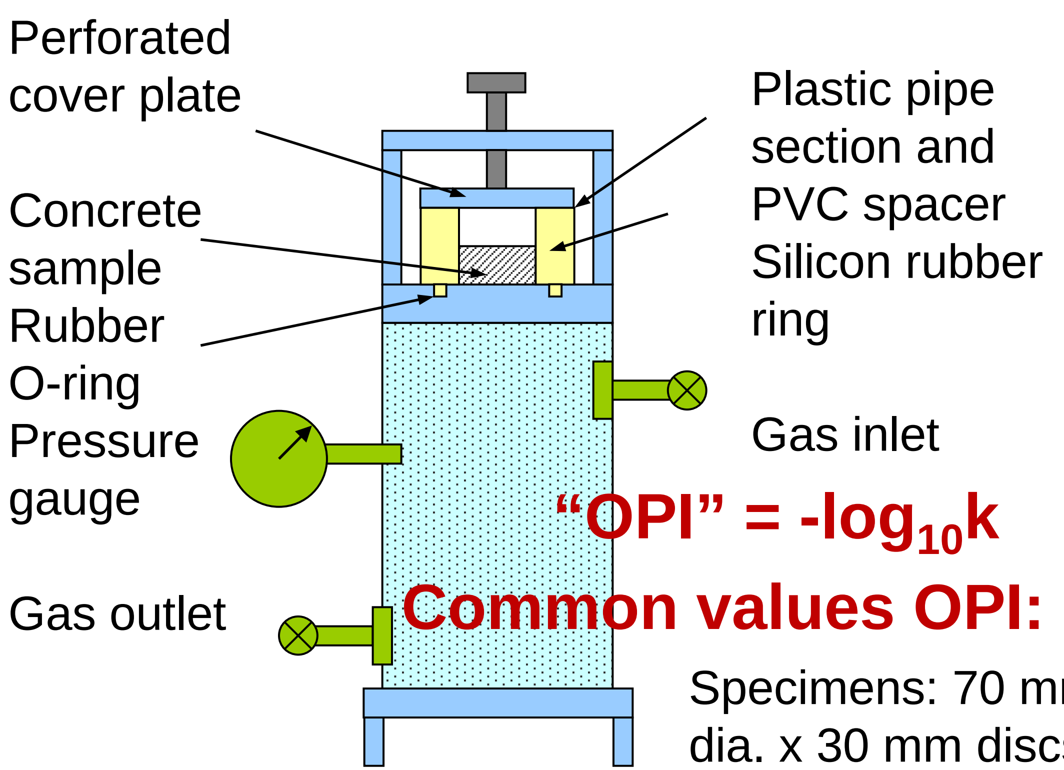
Review of:

- **DI Tests**
- **Service Life Models**

(Developed in the SA Durability Programme)

Oxygen Permeability Index (OPI) Test

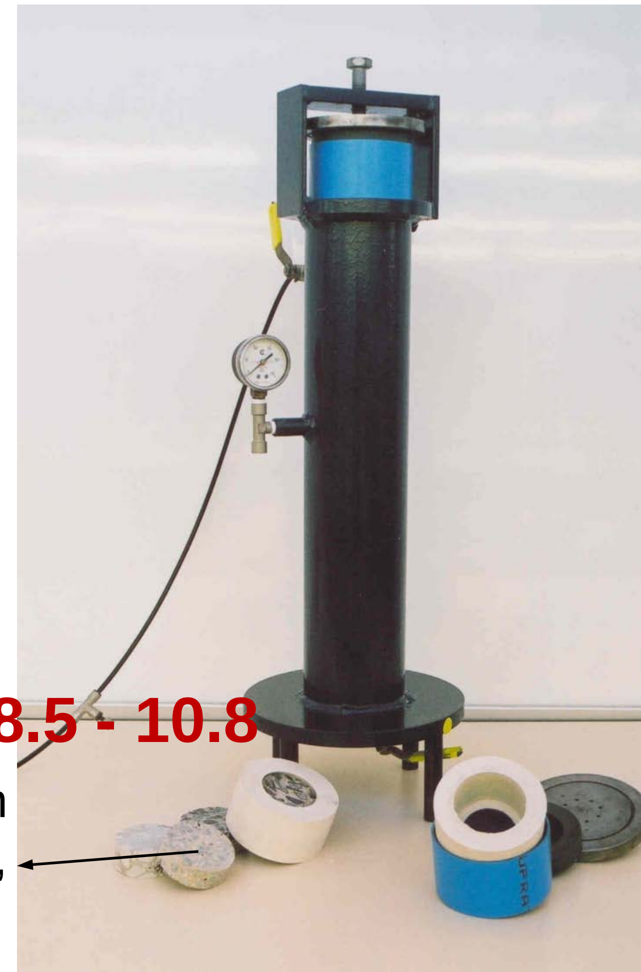
Used to control carbonation resistance



"OPI" = $-\log_{10}k$

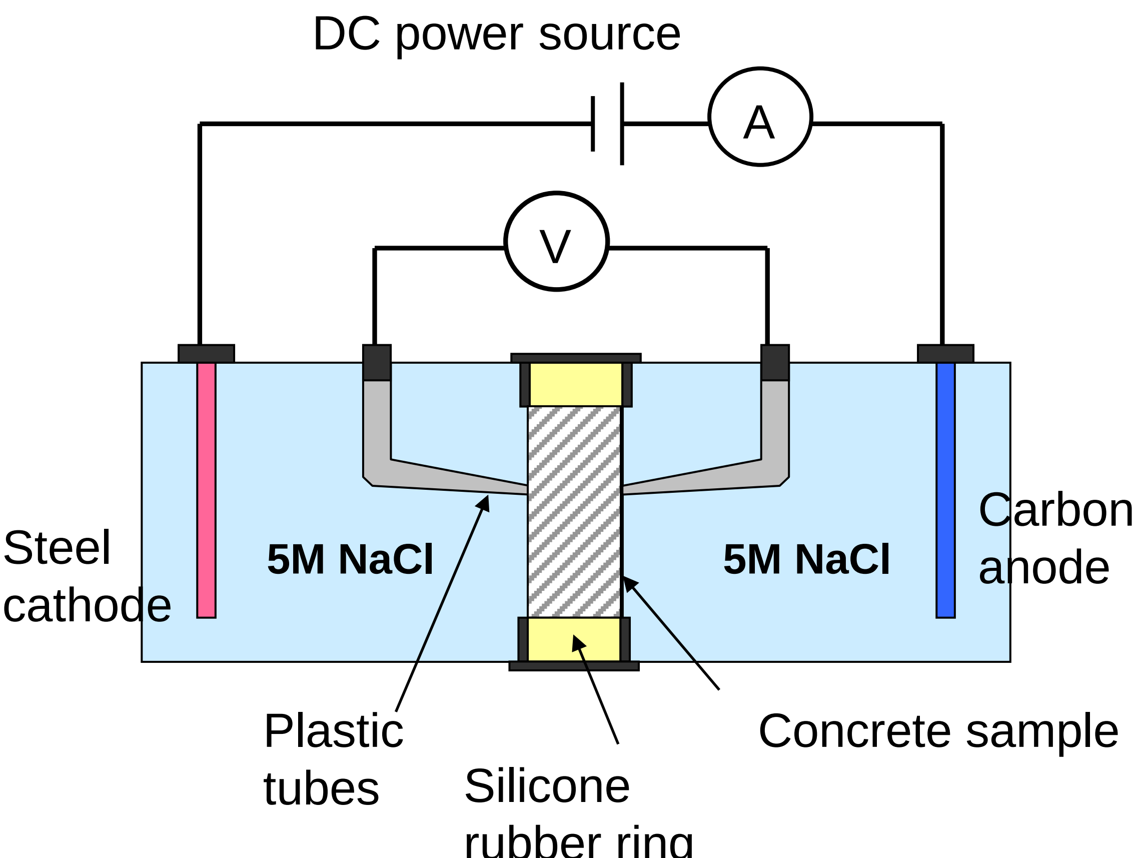
Common values OPI: 8.5 - 10.8

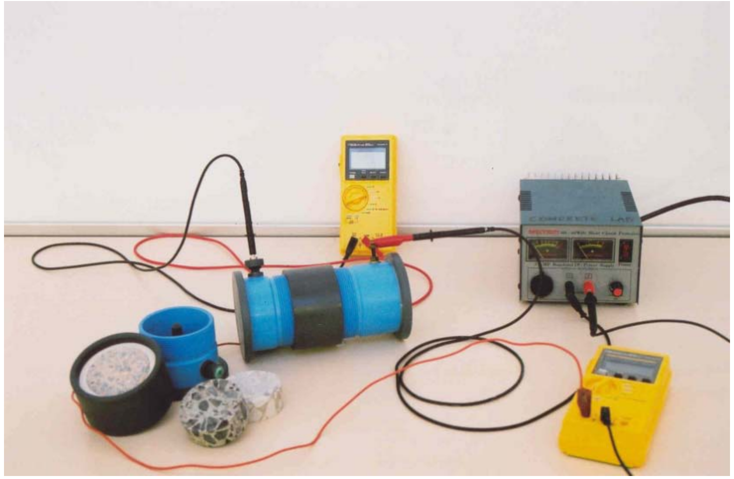
Specimens: 70 mm dia. x 30 mm discs, pre-conditioned



Chloride Conductivity Index (CCI) Test

Used to control chloride resistance





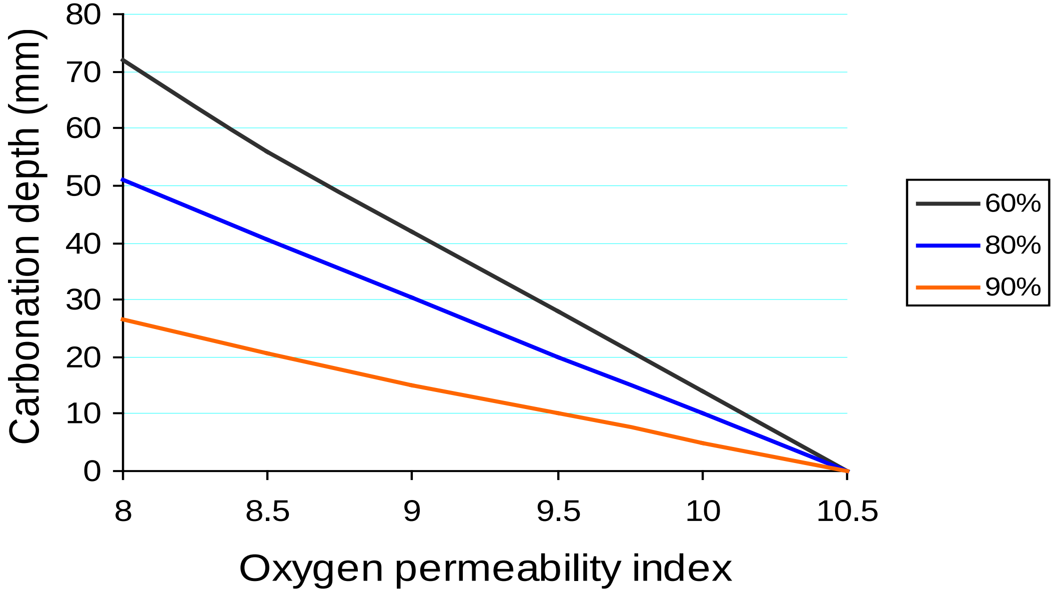
$$\sigma = \frac{i \cdot t}{V \cdot A}$$

Common values CCI: 0.5 – 2.5 mS/cm

Service life models

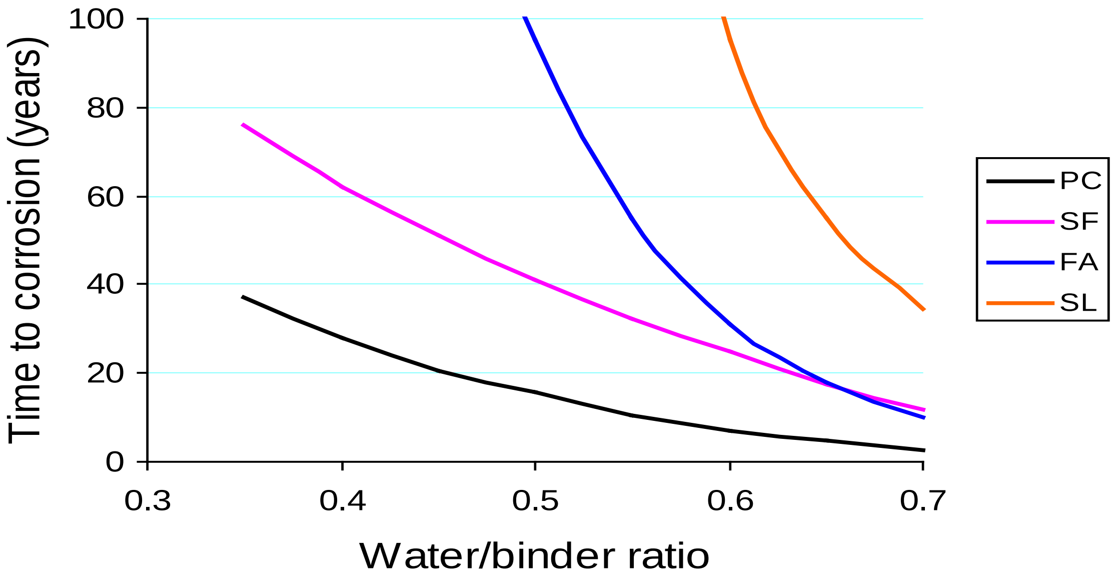
- Initiation models:
  - SLM for carbonation resistance, using 28-day OPI as a parameter
  - SLM for chloride resistance, using 28-day CCI as input to a Fickian model
- Account for material type and environment
- Integrated approach: DI parameters are used
  - In design, via the SLMs
  - In specification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

Service Life Models using Durability Indexes



Carbonation Predictions (50 years)

Chloride predictions: Time to corrosion – Very severe exposure



Criteria for establishing performance criteria

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) – dealt with later

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 measured on actual concrete
  - Cover 'quantity' represented by cover thickness – also measured in situ

Items in red are the Owner's decisions

Design methodology can be applied to two conditions:

1. ‘Deemed to Satisfy’ approach
   (based on ‘standard’ sets of design conditions)

2. Rigorous approach – only briefly touched on here

Reinforcement Cover

- Too little – not enough protection
- Too large – cracking can occur
- Typical Range: 25 - 75 mm
- Deemed to Satisfy: ‘standard’ cover selected for
  - Carbonation: 30 mm
  - Seawater: 50 mm

Cover checked by covermeter surveys post-construction

Design life (after 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 <u>at the level of the steel.</u>

Seawater (marine structures)
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

Carbonation – ‘Deemed to Satisfy’

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 Environment - 'Deemed to Satisfy'

- 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

Examples of Implementation: Rigorous Approach

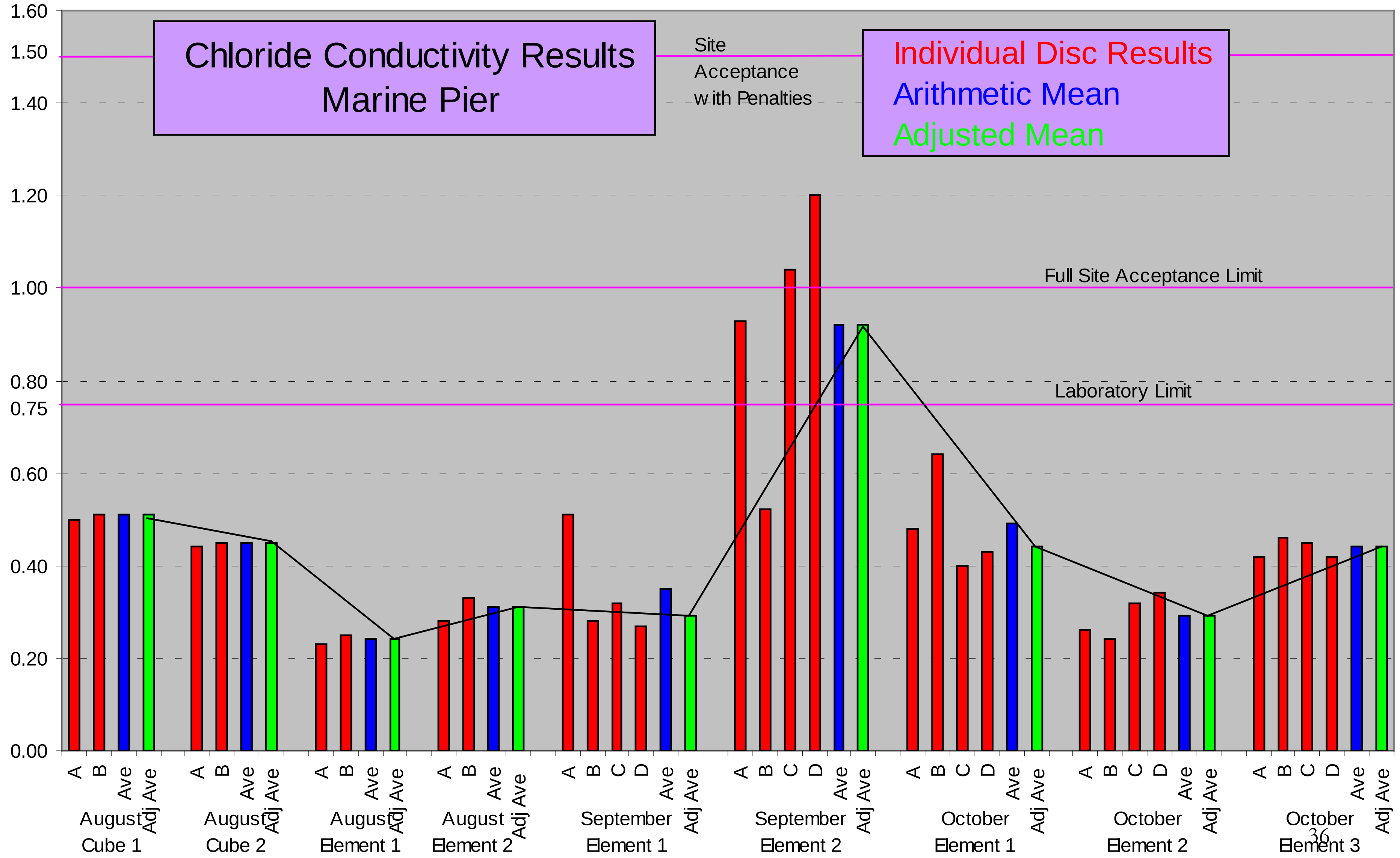
Marine Struct. 50-y design life		Max. chloride conductivity (mS/cm) for various binder types		
Exposure class (based on EN 206)	**Cover (mm)**	**100% CEM I**	**30% fly ash**	**50% Corex slag**
XS3b: Tidal, splash and wetted spray zones, exposed to abrasion	40	0.45	0.75	1.05
	60	0.95	1.35	1.95
	80	1.30	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			Impractical mixes; concrete grade > 60 MPa	
Note 'trade-off' between mat'l. quality and cover			Not recomm.: < 30 MPa, and/or w/b > 0.55	
			Acceptable: Grades from 30 to 60 MPa	

Example of Implementation: Site construction & DIs

Example of Implementation: Site construction & DIs

- Aggressive marine conditions in Durban
  - Sub-tropical, high temps. and RH, strong salt-laden on-shore winds
- Procedure:
  - Develop concrete mix in lab first to provide required level of performance (DI testing)
  - Take DI samples from structure during construction and test
    - Requirements for these less stringent than lab values
  - Sampling more frequent at start of construction, to assist contractors to achieve required performance
- Example follows of Pier Construction: CC values

U'Shaka pier


Chloride Conductivity Results
Marine Pier
Individual Disc Results
Arithmetic Mean
Adjusted Mean
Site Acceptance with Penalties
Full Site Acceptance Limit
Laboratory Limit
1.60
1.50
1.40
1.20
1.00
0.80
0.75
0.60
0.40
0.20
0.00
A B Ave Adj Ave
August Cube 1
August Cube 2
August Element 1
August Element 2
A B C D Ave Adj Ave
September Element 1
September Element 2
October Element 1
October Element 2
October Element 3

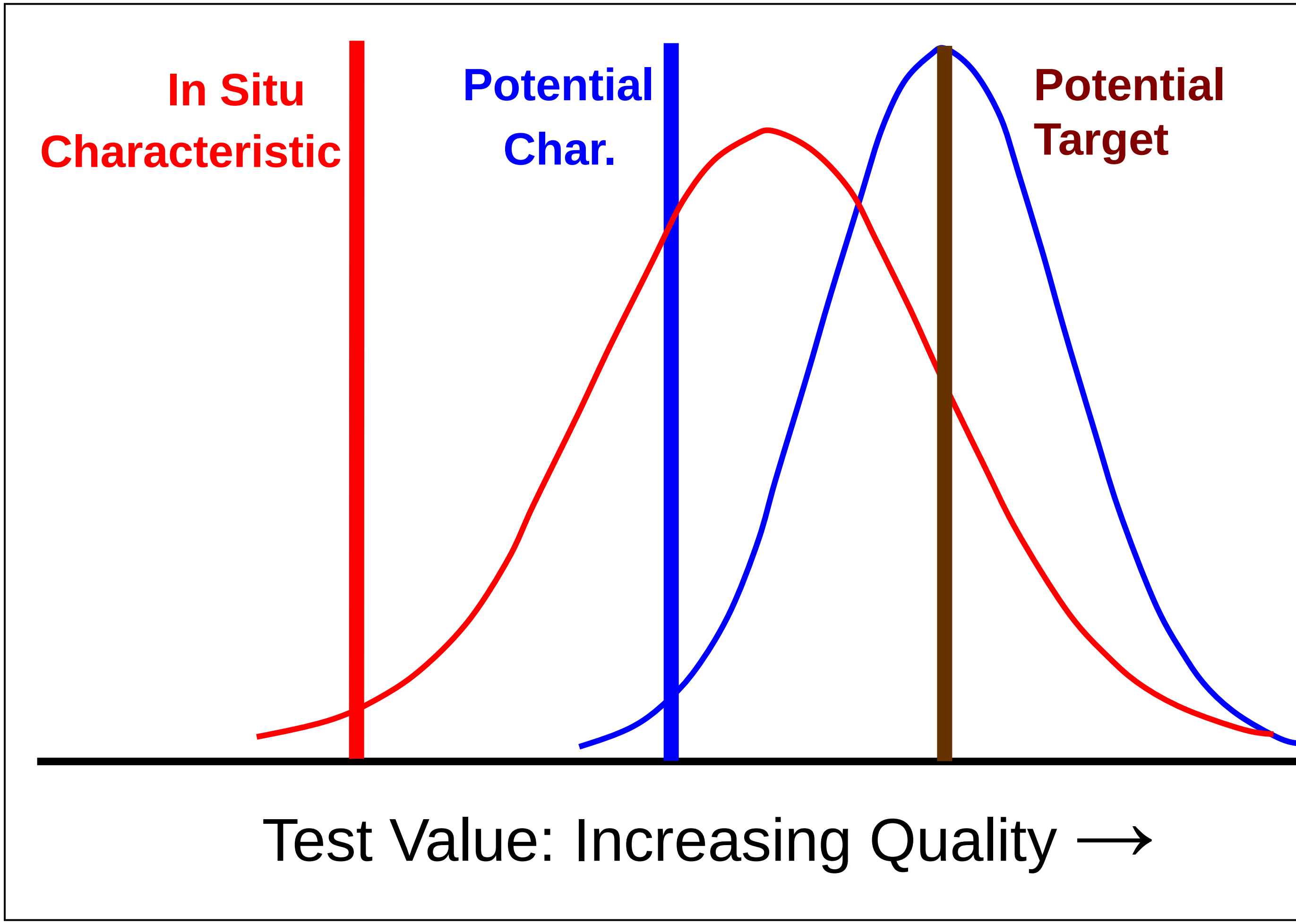
Performance-based durability specifications and site quality control

Material Potential vs. As-Built Construction Quality

- Specifications are concerned with as-built quality BUT

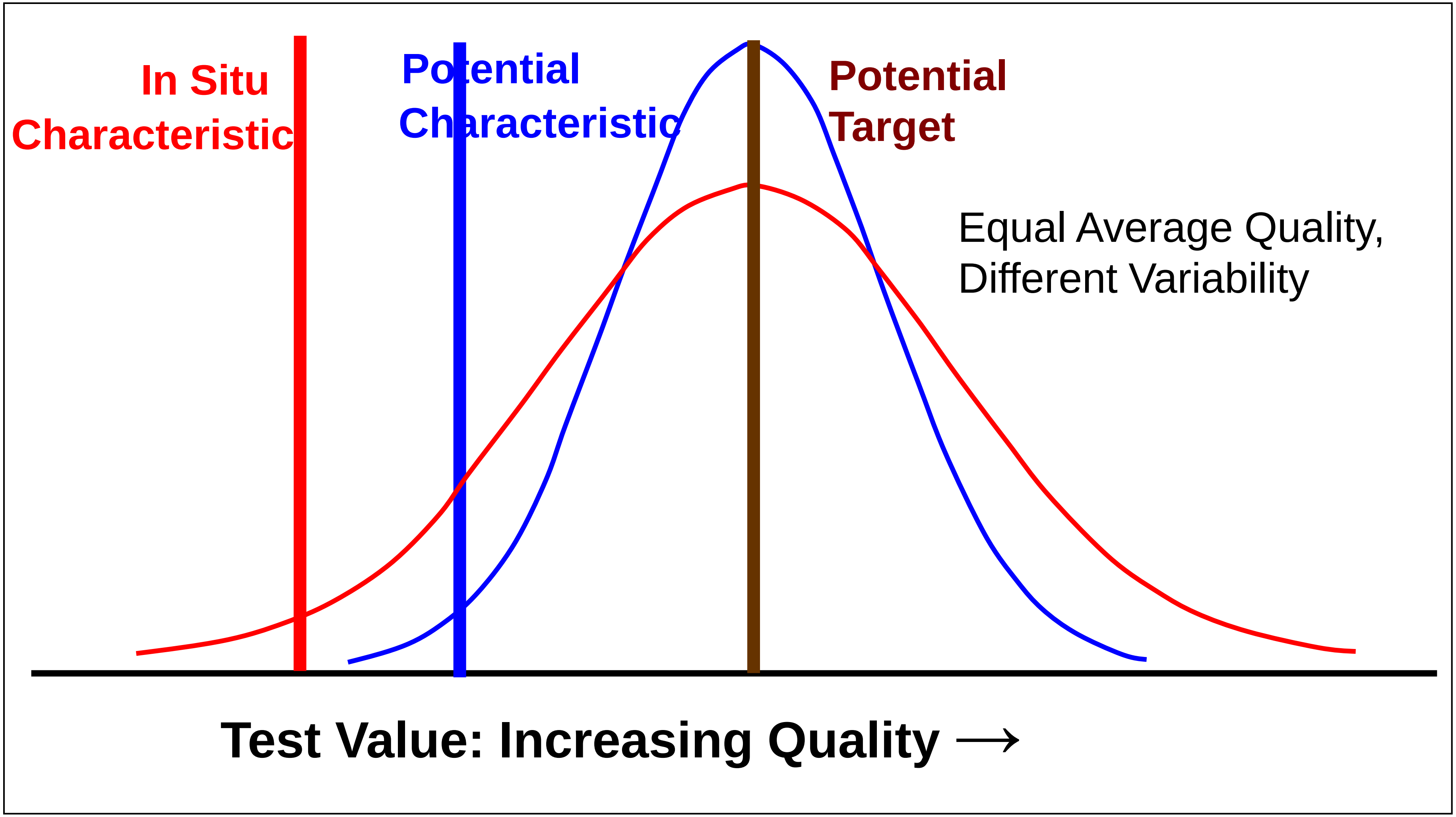
  Concrete production process cannot be ignored
- Two stages in addressing concrete of desired quality:
  - material production & supply – material potential
  - concrete placing and finishing – as-built quality
    - Deficiencies can arise in both stages
- Therefore, we need a two level quality control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

Material Potential vs As-Built Values

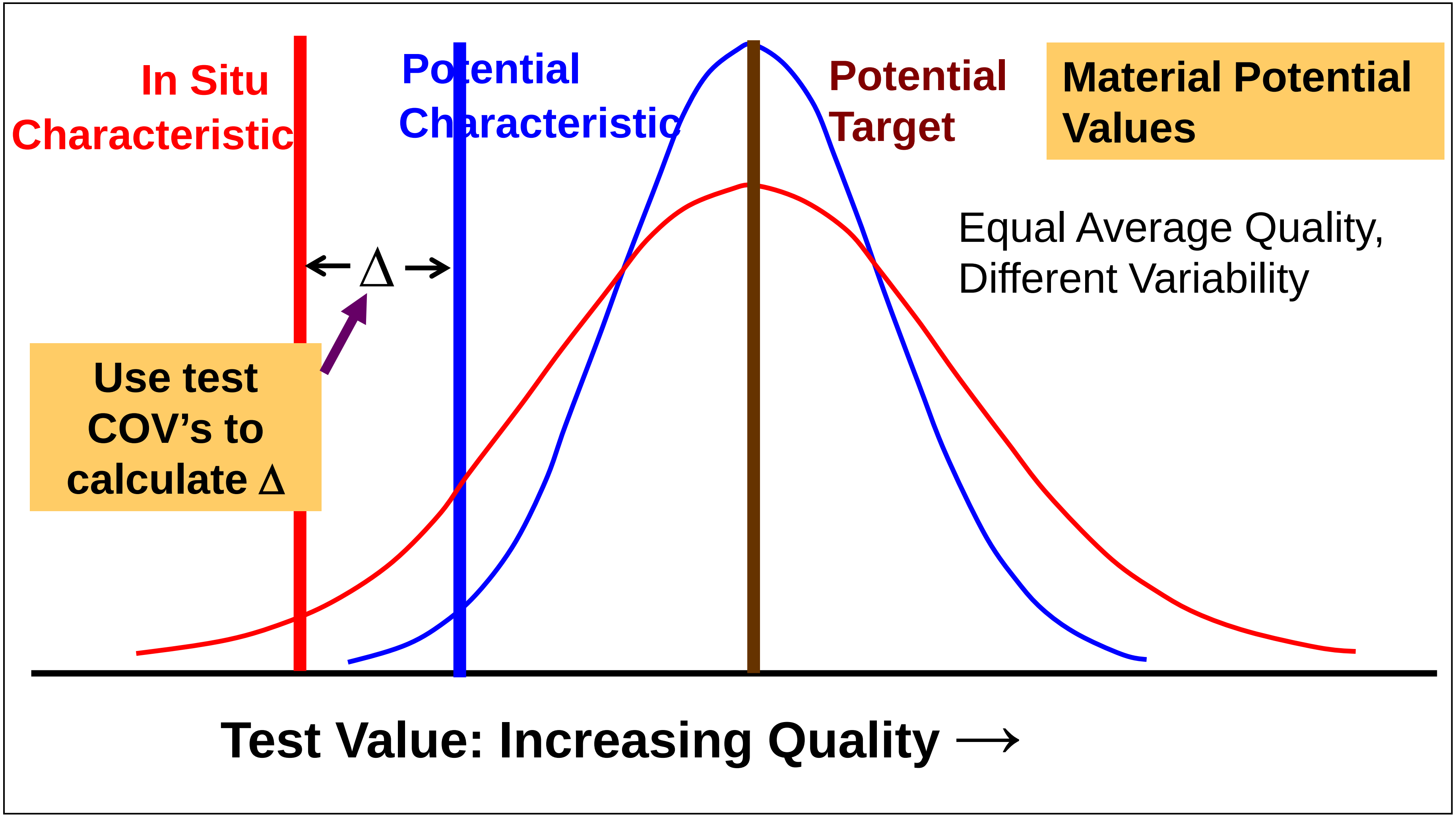


These values need to be established by testing of both “laboratory” specimens and samples from the structure.

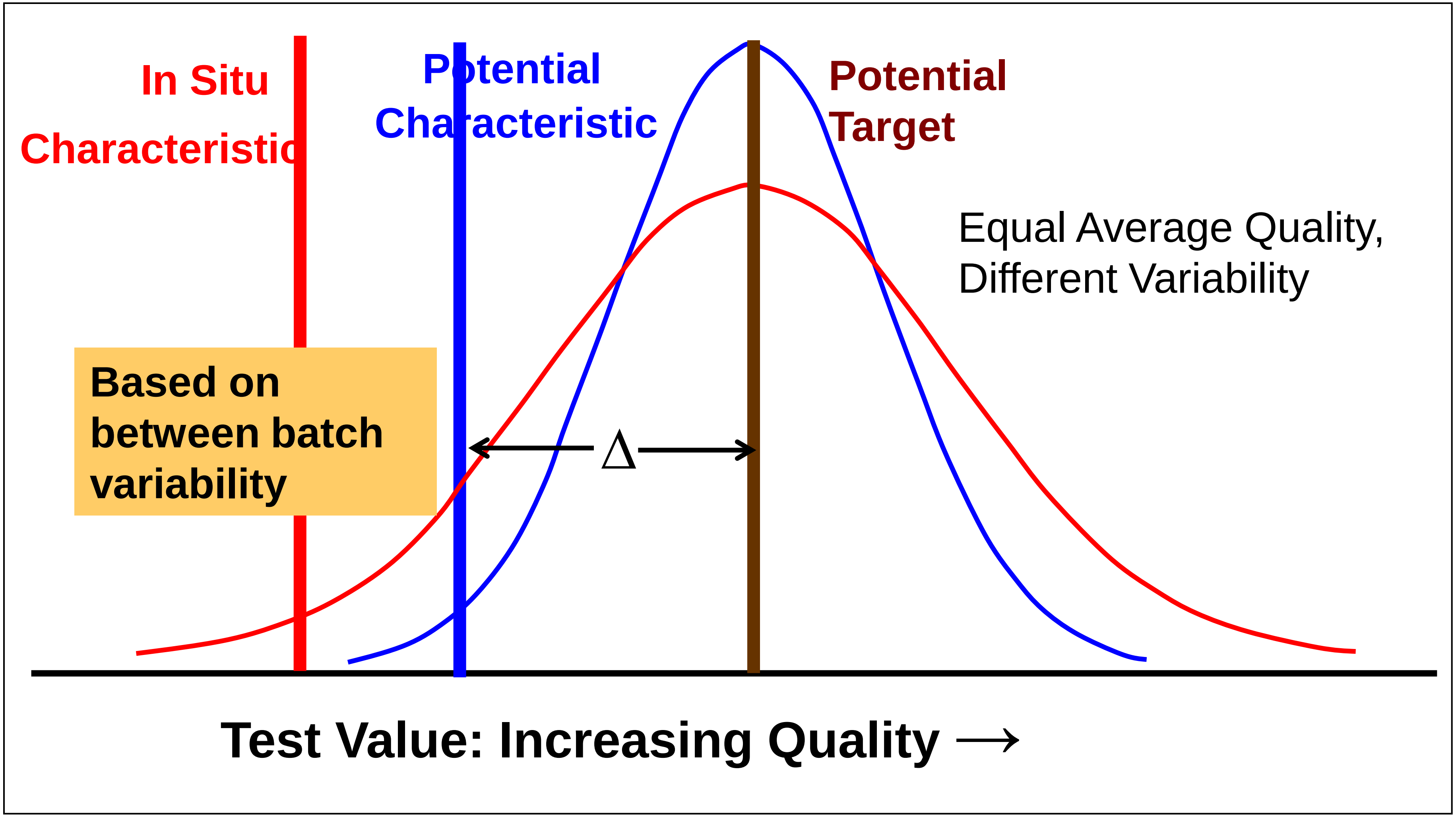
Assumption: same averages for Material Potential and As-Built Values



As-built vs. Material potential



Potential target vs. characteristic



Developing margins

- Characteristic value is defined in a manner similar to that for strength – a given probability that the average of three consecutive tests will be worse than this value
- Serviceability criteria, not Ultimate
- 1:10 vs. 1:100
- Based on measured COV's

COVs of test values – from Site Experience

- Based on studies of laboratory and in situ concrete performance
- Found that:
  - Average values inconsistent – may be greater or less than potential
  - Increased variability of as-built results vs. laboratory concrete

	COV	
	Chloride Conductivity	OPI
Laboratory	5 %	1 %
As-Built	14 %	2 %

Material potential results

- Evaluated from cubes cured in a standard manner
- Requires a higher level of performance

$$OPI_{Mat'l} \geq OPI_{Specified} + 0.10$$

$$CC_{Mat'l} \leq 0.90 CC_{Specified}$$

As-built results

- Evaluate the as-built final product
- Tested on cores taken from the structure (or test panels) at 28 days
- Must achieve the minimum values determined by owner

$$OPI_{As\ Built} \geq OPI_{specified}$$

$$CC_{As\ Built} \leq CC_{Specified}$$

Target vs. Characteristic values

- As is done with strength
- Not as stringent criteria (1:10 vs. 1:100)
- OPI:

$$OPI_{Target} = OPI_{char} + 0.22$$

- Chloride conductivity:

$$CC_{Target} = 0.90\ CC_{characteristic}$$

$$CC_{Target} = 0.82\ CC_{char} + 0.20$$

Example

Owner's/Designer's Decisions

Environment: Tidal, Splash, Spray Zone, Not Exposed to Abrasion: XS3a ?

Service Life: 50 years

Nominal Cover: 50 mm

➔ Use Deemed to Satisfy Approach

Common Structure ?

Example: Chloride Conductivity (mS/cm)

As-built values vs. Potential Target Values

(hypothetical case)

Level	70:30 CEMI:FA	50:50 CEMI:GGBS	50:50 CEMI:GGCS	90:10 CEM I:CSF
XS3a	1.35	1.60	1.95	0.45
Pot'l Char.	1.22	1.44	1.76	0.41
Pot'l Target	1.09	1.30	1.58	0.37

x 0.90

x 0.90 or x 0.82+0.20

- Based on the preceding table, concrete mix is designed (also for strength etc.)
- Mix tested for the production quality (‘Material Potential’)
- As-built values also tested to check conformity with specification

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

Developments in re-drafting SA concrete codes

- Moving towards performance-based approaches to durability:
  - Aim at limiting the environmental consequences on structure to acceptable targets during the service life
  - Advocate use of service life prediction models
  - Quantify environmental deterioration and provide output in terms of the expected material quality
- Designer makes choices of selecting a suitable material (conventional, new or marginal) that will meet the requirements within the predefined acceptable level
- Specified material quality then verified on site using durability tests that characterise that quality

Current proposal (for durability)

- Based on Eurocodes (historical – BS codes as basis)
- Adopt EN 206 and EN 13670 (Execution of concrete structures)
- Redraft SA Code:
  - Define exposure class and nominal design life
  - Work within a reliability framework
    - durability provisions drafted, varying from simple approaches (e.g. avoid deterioration by coatings) to full probab. approach
    - incrementally improve the code as knowledge develops
  - Provide a 'National Annex' type document to elaborate EN 206 - interpretive' document for practical guidance to the engineer

E.g. In the UK, Complementary standard to EN 206 is BS 8500

- specifies constituent materials, etc

Proposal

- Initially, code to comprise only ‘deemed to satisfy’ provisions – covering <u>two alternatives</u>:
  - Guidance on material and structural parameters (i.e. max w/c, min cement content, strength class, cover)
    - account for generic binder type and environment
    - set limiting values (necessarily conservative) - justifiable in terms of a service life approach
    - calibrated as far as possible against existing SA service life models
    - recognition of design life
  - Limiting DI values (linked to service life models) – for carbonation and chlorides should require on-site evaluation for achieving as-built durability
- Plus: linkage with structural class

Closure

- Presentation has described the 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
- Work is advancing on completely re-drafting the SA Concrete Code based on the EN codes but incorporating local practice

Thank You!

…and good luck with preparations for World Cup 2014!

…and of course, preparations for the more important event - RILEM Week 2014 in Brazil!