Performance-based durability design and specifications for concrete structures

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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 actual as-built quality 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

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

<table>
<thead>
<tr>
<th>STEPS FOR DEVELOPMENT (5 to 7)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Durability design</strong></td>
<td><strong>Durability specification</strong></td>
</tr>
<tr>
<td><strong>5. Establish limitations of test applicability</strong></td>
<td></td>
</tr>
<tr>
<td>DI tests: moderate to high-grade concretes; not valid for very HSC, special concretes.</td>
<td>Specs. cover ‘typical’ normal construction</td>
</tr>
<tr>
<td><strong>6. Ensure production control and acceptance testing</strong></td>
<td></td>
</tr>
<tr>
<td>Differentiate between quality ‘as-supplied’ (manufacturer’s responsibility) &amp; as-built (constructor’s responsibility).</td>
<td>Two-level requirement: ‘as-supplied’ vs. ‘as-built’ DI s. (Owner requires final ‘as-built’ values only)</td>
</tr>
<tr>
<td><strong>7. Conduct full-scale trials and long-term monitoring to confirm conformity requirements</strong></td>
<td></td>
</tr>
<tr>
<td>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.</td>
<td></td>
</tr>
</tbody>
</table>
South African Framework – “Durability Index Approach”

MATERIAL INDEXING
Characterization of concrete (surface layer) using easily measured physical properties, such as permeability and sorptivity

DIRECT DURABILITY TESTING
Suite of accelerated tests (lab)
Long-term tests (lab or site-based)

Correlations

STRUCTURAL PERFORMANCE
Evaluation of structural performance;
Consequences of deterioration;
Management of economic strategies

Correlations

QUALITY CONTROL

PREDICTION
Aggressiveness of micro- and macro-environment

FUNDAMENTAL MECHANISTIC STUDIES

ENVIRONMENT
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
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Review of:

- DI Tests
- Service Life Models

(Developed in the SA Durability Programme)
Oxygen Permeability Index (OPI) Test

Used to control carbonation resistance

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

“OPI” = -log_{10}k

Common values OPI: 8.5 - 10.8
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)

<table>
<thead>
<tr>
<th>Design Life Category</th>
<th>Indicative Design Working Life</th>
<th>Examples of Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 years</td>
<td>Temporary</td>
</tr>
<tr>
<td>2</td>
<td>10 to 25 years</td>
<td>Replaceable Structural Parts</td>
</tr>
<tr>
<td>3</td>
<td>15 to 30 years</td>
<td>Agricultural and Similar Structures</td>
</tr>
<tr>
<td>4</td>
<td>50 years</td>
<td>Buildings and Other Common Structures</td>
</tr>
<tr>
<td>5</td>
<td>100 years</td>
<td>Monumental Building Structures, &amp; Civil Engineering Structures</td>
</tr>
</tbody>
</table>
## Carbonation

### Environmental Categories (after EN 206)

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>XC1</td>
<td>Permanently Wet or Permanently Dry</td>
</tr>
<tr>
<td>XC2</td>
<td>Wet, Rarely Dry</td>
</tr>
<tr>
<td>XC3</td>
<td>Moderate Humidity (60-80 %)</td>
</tr>
<tr>
<td>XC4</td>
<td>Cyclic Wet and Dry</td>
</tr>
</tbody>
</table>

Categories refer to the moisture state at the level of the steel.
Seawater (marine structures)

Environmental Categories (after EN 206)

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS1</td>
<td>Exposed to airborne salt, &lt; 5 km from sea, east &lt;15 km from sea west of Cape Agulhas</td>
</tr>
<tr>
<td>XS2a</td>
<td>Permanently Submerged</td>
</tr>
<tr>
<td>XS2b</td>
<td>XS2a + exposed to abrasion</td>
</tr>
<tr>
<td>XS3a</td>
<td>Tidal, splash and wetted spray zones</td>
</tr>
<tr>
<td>XS3b</td>
<td>XS3a + exposed to abrasion</td>
</tr>
</tbody>
</table>
# Carbonation – ‘Deemed to Satisfy’

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

<table>
<thead>
<tr>
<th></th>
<th>Common Structures</th>
<th>Monumental Structures (1)</th>
<th>Monumental Structures (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service Life</td>
<td>50 years</td>
<td>100 years</td>
<td>100 years</td>
</tr>
<tr>
<td>Minimum Cover</td>
<td>30 mm</td>
<td>30 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Minimum OPI</td>
<td>9.70</td>
<td>9.90</td>
<td>9.70</td>
</tr>
</tbody>
</table>

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)

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

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

Maximum w/b of 0.55

Maximum Chlor. Cond. Values (mS/cm): (100y life)
**Examples of Implementation: Rigorous Approach**

<table>
<thead>
<tr>
<th>Marine Struct. 50-y design life</th>
<th>Max. chloride conductivity (mS/cm) for various binder types</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exposure class (based on EN 206)</strong></td>
<td><strong>Cover (mm)</strong></td>
</tr>
<tr>
<td>XS3b: Tidal, splash and wetted spray zones, exposed to abrasion</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td>XS0b: Airborne salt in an exposed near-shore marine location</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
</tbody>
</table>

**Legend**

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

**Note ‘trade-off’ between mat’l. quality and cover**
Example of Implementation: Site construction & DIs

U’Shaka pier - Durban
Example of Implementation: Site construction & Dls

- 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
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U’Shaka pier

Chloride Conductivity Results
Marine Pier

Individual Disc Results
Arithmetic Mean
Adjusted Mean

August
Cube 1
August
Cube 2
August
Element 1
August
Element 2
September
Element 1
September
Element 2
October
Element 1
October
Element 2
October
Element 3

Site
Acceptance
with Penalties

Full Site Acceptance Limit

Laboratory Limit
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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

In Situ Characteristic
Potential Char.
Potential Target

Test Value: Increasing Quality →

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

Test Value: Increasing Quality →

Equal Average Quality, Different Variability
As-built vs. Material potential

Test Value: Increasing Quality →

Use test COV’s to calculate $\Delta$

Equal Average Quality, Different Variability

Material Potential Values

Potential Characteristic

Potential Target

In Situ Characteristic

$\Delta$
Potential target vs. characteristic

Equal Average Quality, Different Variability

Based on between batch variability

Test Value: Increasing Quality →
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

<table>
<thead>
<tr>
<th>COV</th>
<th>Chloride Conductivity</th>
<th>OPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td>5 %</td>
<td>1 %</td>
</tr>
<tr>
<td>As-Built</td>
<td>14 %</td>
<td>2 %</td>
</tr>
</tbody>
</table>
Material potential results

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

\[ \text{OPI}_{\text{Mat'l}} \geq \text{OPI}_{\text{Specified}} + 0.10 \]
\[ \text{CC}_{\text{Mat'l}} \leq 0.90 \text{CC}_{\text{Specified}} \]
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

\[ \text{OPI}_{\text{As Built}} \geq \text{OPI}_{\text{specified}} \]

\[ \text{CC}_{\text{As Built}} \leq \text{CC}_{\text{Specified}} \]
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Target vs. Characteristic values

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

\[ \text{OPI}_{\text{Target}} = \text{OPI}_{\text{char}} + 0.22 \]

- Chloride conductivity:

\[ \text{CC}_{\text{Target}} = 0.90 \text{CC}_{\text{characteristic}} \]
\[ \text{CC}_{\text{Target}} = 0.82 \text{CC}_{\text{char}} + 0.20 \]
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)

<table>
<thead>
<tr>
<th>Level</th>
<th>70:30 CEMI:FA</th>
<th>50:50 CEMI:GGBS</th>
<th>50:50 CEMI:GGCS</th>
<th>90:10 CEM I:CSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS3a</td>
<td>1.35</td>
<td>1.60</td>
<td>1.95</td>
<td>0.45</td>
</tr>
<tr>
<td>Pot’l Char.</td>
<td>1.22</td>
<td>1.44</td>
<td>1.76</td>
<td>0.41</td>
</tr>
<tr>
<td>Pot’l Target</td>
<td>1.09</td>
<td>1.30</td>
<td>1.58</td>
<td>0.37</td>
</tr>
</tbody>
</table>

- XS3a values are multiplied by 0.90 or 0.90 or 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 **two alternatives**:
  - 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
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!