Assessing the Durability and Service Life of Concrete Structures

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“They Showed the Way for Me.”

- Practical Approach
- Concrete Technology
- Breadth of Knowledge
- Non-destructive Testing
- Deterioration Mechanisms
- Cementitious Materials
- Microstructure & Modelling

Still a student

The Queen’s University of Belfast, Northern Ireland, U.K.
A Salute to My Predecessor

Chair in Structural Engineering & Head of School of Civil Engineering

1968-1978

2014-
Outline of Presentation

- Rationale for assessing the durability and service life of structures
- Novel *in situ* permeation tests
- Electrical resistance and corrosion sensors
- Fibre optic chemical sensors
- Dynamic structural/condition monitoring
- Prediction of the performance
- Concluding remarks
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Clifton Suspension Bridge – Aero-elastic Behaviour

Similar to Tacoma Narrows Bridge. Damage is when the structure does not perform as intended; could be considered as a failure.
Montreal Bridge Collapse

Canada, 2006: 5 people were killed in a bridge collapse caused by road salt induced corrosion
Cover Concrete - Critical for Concrete Durability

Ingress from the environment

H₂O  CO₂  O₂  Cl⁻  SO₃⁻

Sorptivity  Permeability  Diffusivity

Cover Concrete

Poorer quality “covercrete” due to:
- Segregation
- Over-compaction
- Lack of curing
- Bleeding
- Over-finishing
- Microcracking
Surface is the Achilles Heel of Concrete!
Need for Performance Tests

- Propagation of deterioration
- Service life

Changes of material properties

Duration of Exposure

- Initiation period
- Active period
- FINAL STAGE

Degree of Deterioration

Duration of Exposure:
- $t_0$
- $t_f$

Justifies:
- Early age testing
- Frequent intermittent testing and/or continuous monitoring
An Holistic Approach for Assessing Structures

1. *In Situ* Tests for assessing the durability
   - Gas & water Transport
   - Ionic Transport

2. Sensors for structural health monitoring

3. Prediction of the performance

4. Dynamic structural/condition monitoring

Oresund Bridge between Sweden and Denmark
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In Situ Permeation Tests

Permeation Properties

- Absorption
- Permeability
- Diffusion

- Received ACI/James Instruments NDT award in 1991 and 1998
- Established Amphora NDT Ltd., a University spin-out in 2002 to manufacture and market test instruments for the construction industry
Application of Test Technologies in China

Testing Concrete Quality with Autoclam in Bird’s Nest by CRIBC
Application of Test Technologies in China

Testing Concrete Quality with Autoclaim in Dayawan Nuclear Power Station by CRIBC
Application of Test Technologies in China

Testing Concrete Quality with Autoclam in Beijing-Tianjin Railway Project by CRIBC
In the Harbin-Dalian Railway construction, The PERMIT was used to assess the construction quality.
In the Qingdao Bay Bridge, the effect of different methods for improving the resistance to the penetration of chloride ions of cover concrete was investigated by Tsinghua University.
### Typical Values of Transport Properties

<table>
<thead>
<tr>
<th>Coefficient of transport properties</th>
<th>Concrete</th>
<th>Variance (CoV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poor</td>
<td>Normal</td>
</tr>
<tr>
<td>$K_{gas}$ (m$^2$)</td>
<td>$&gt;10^{-13}$</td>
<td>$10^{-14}$-$10^{-15}$</td>
</tr>
<tr>
<td>$K_{water-s}$ (m/s)</td>
<td>$&gt;10^{-11}$</td>
<td>$10^{-11}$-$10^{-13}$</td>
</tr>
<tr>
<td>$K_{water-ns}$ (m/s)</td>
<td>$&gt;10^{-10}$</td>
<td>$10^{-10}$-$10^{-12}$</td>
</tr>
<tr>
<td>$D_s$ (m$^2$/s)</td>
<td>$&gt;10^{-11}$</td>
<td>$10^{-11}$-$10^{-12}$</td>
</tr>
<tr>
<td>$D_{nssd}$ (m$^2$/s)</td>
<td>$&gt;10^{-11}$</td>
<td>$10^{-11}$-$10^{-12}$</td>
</tr>
<tr>
<td>$D_{ssm}$ (m$^2$/s)</td>
<td>$&gt;10^{-11}$</td>
<td>$10^{-11}$-$10^{-12}$</td>
</tr>
<tr>
<td>$D_{nssm}$ (m$^2$/s)</td>
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Electrical Resistance and Corrosion Sensors

Covercrete Electrode Array

Electrode Array and Corrosion Rate Sensor

Joint research with Prof John McCarter and his team at Heriot-Watt University Edinburgh, Scotland
Site Investigation at Dornoch, Scotland
Site Investigation at Dornoch, Scotland

PC: CEM I-42.5N
GGBS: CEM III/A-42.5N
PFA: CEM II/B-V-42.5N
Remote Data Collection Using Wireless

Solar Panel
Data Logger
& Multiplex Unit
Power Supply
Site Investigation at Dornoch, Scotland (Low Level Location – XS2)
Integrated Sensor System in
Hangzhou Bay Bridge Monitoring Station

Hangzhou Bay and the Bridge

Hangzhou Bay bridge connects Jiaxing and Ningbo municipalities of Zhejiang province, China. 35.6km (22 mile) long. Wave height 9m, wind speed >30mph.
Hangzhou Bay Bridge Monitoring Station

Hangzhou Bay Bridge Service Centre

During construction

Monitoring station located at the service centre

Completed
Hangzhou Bay Bridge Monitoring Station

Atmospheric zone

Splash zone

Tidal zone

Control station

Weather station @ Level 2
Hangzhou Bay Bridge Monitoring Station

Installation of blocks    Installation of control unit
Integrated Sensor System in Hangzhou Bay Bridge Monitoring Station

Schematic of the total monitoring station

- Temperature sensors
- Electrical resistivity sensors
- Corrosion sensors
- Weather Station
- Monitoring Station
- Cloud computing
- Remote PC
Weather Data From the Bridge

QUB Monitoring Stations
HANGZHOU BAY BRIDGE

Hangzhou Bridge-China - 23/6/2012

- Temperature
  - 22.2°C (High)
  - 23.2°C (Low)
- Wind
  - 9.6km/h (Daily)
  - 13km/h (Max)
- Wind Chill
  - 9W
  - 8W
- Humidity
  - 73.7%
  - 97%
- Dew Point
  - 22.7°C

Barometer
- 999.8hPa
- 0.39hPa/h

Journal of Construction and Building Materials

- New approach for shrinkage prediction of high-strength lightweight aggregate concrete
  - June 25, 2012
- Properties of multi-strength grade EPS concrete containing silica fume and rice husk ash
  - June 25, 2012
- Application of non-destructive geomatic techniques and FDTD modeling to metrological analysis of stone blocks in a masonry wall
  - June 25, 2012
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Chloride Ingress and Its Effect

Chloride content > 0.2 to 0.6 % by weight of cement

pH ~ 13

Types of Corrosion:
General and Pitting (depends on $O_2$ availability)

Protective layer is destroyed

Binding of Chlorides $\rightarrow$ Calcium chloro-aluminate

C-S-H, C-A-H

Ca(OH)$_2$, Cl$^-$
Effect of Carbonation

- Loss of passivity
  - pH decreases
  - pH ~ 13

- Formation of rust

Advance of carbonation front → cracking of concrete
Sensors for Structural Health Monitoring

Electrical Resistivity Sensors
- Moisture movement
- Chloride ingress
- Carbonation
- Corrosion

Fibre Optic Sensors
- RH
- pH
- Chlorides
- Temperature
- Strain

Collaborative Research With Prof K Grattan and Prof T Sun from City University London

Collaborative Research With Prof J McCarter from Heriot-Watt University Edinburgh
Fibre Optic Sensors for SHM

Humidity and Temperature Sensors

pH and Chloride Sensors
Set-Up for Chemical Sensors

Light Source

Spectrophotometer

Probe
Placement of pH FOS in Concrete

Probes prepared by covering with moisture permeable layer before placing in mould
pH Measured Using FOS pH Probe in Hardened Mortar
pH Variations During 6 Weeks of Carbonation

Graph $y = x$

pH measured using glass pH electrode

pH measured using fibre optic pH sensor
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Investigation of Aero-elastic Behaviour in Bridges

1. Dynamic Structural/Condition Monitoring

Clifton Suspension Bridge

2. Modal & Identification Analysis

3. Flutter/Dynamic Instability Propensity

Negative damping increases with increase in wind speed, leading to the collapse of the bridge at some point in time.

Aero-dynamic problems are equally applicable to new bridges

4. Transfer of Knowledge (for other bridge owners)

Ting Kau Bridge in Hong Kong
Investigation of Aero-elastic Behaviour in Bridges

5. Public Engagement/Dissemination

Real case studies, such as the Clifton Suspension Bridge could be used to educate bridge designers, builders and operators.

This strategy could lead to today’s bridges becoming monuments of tomorrow.
SHM Applied to Monitoring Earthquake Behaviour

Road Tunnel in La Polvora, Chile

Metro Line in Santiago, Chile

Wireless Inertial Measurement Units
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Models for Predicting the Performance

Exposure Parameters

Materials (Ingredients and Proportions)

Virtual Predictions

Data from SHM

Data of transport properties

Estimation of service life

Service Life Models

Hymostrut
μiC
Stadium
NIST

Life365
Stadium
NIST
ClinConc
Duracrete
ClinConc Model for Predicting the Performance

After 1 year

After 7 years

After 50 years
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Role of NDTs and SHM

(1) Useful for early identification of potential problems and addressing them

(2) Decide on time for planned maintenance and repair, or estimate service life
Acknowledgement

- All research colleagues, particularly,
  - academics who were investigators in numerous projects included in this presentation,
  - postdoctoral researchers, postgraduate research students and undergraduate project students who contributed to the research.

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  - European Commission
  - Technology Strategy Board/Innovate UK
Thank You

Any Questions?

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