Concrete Specification and Maintenance Strategy for Marine Structures

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  Honorary Advisor to Standing Committee on Concrete Technology
Content

Part 1 – Specifications for Marine Structures in HK

Part 2 – Maintenance Strategy for Marine Structures
Part 1: Specifications for Marine Structures in HK

- Durability and Design Life of Marine Concrete Structures
- Factors affecting Durability of Marine Structures
- Conventional Specifications for Marine Concrete
- Durability Performance of Conventional Marine Concrete Structures
- Development of Marine Concrete Specification
- Durability Performance of Marine Concrete
- Recommendations to enhance durability performance
Durability

Prof. A.M. Neville, “Properties of Concrete”

It is essential that concrete should withstand the conditions for which it has been designed, without deterioration, over a period of years. Such concrete is said to be durable.
The design life of a structure is taken to be its intended useful life, and will depend on the purpose for which it is required.

Design life for all permanent marine structures should be 50 years.
Highway Structures Over Marine Environment

- 120 year design life
- For major structural elements, design life means without replacement
Factors Affecting Durability of Marine Structures

Internal Factors

• Properties of Concrete
• Quality of Raw Materials
• Strength of Aggregate
• Mix Composition
• Workmanship
• Curing
Factors Affecting Durability of Marine Structures

Other Factors

- Alkali Aggregate Reaction
- Chemical Attack
- Abrasion and Weathering
- Creep and Shrinkage
- Corrosion of Reinforcement
Environments Encountered

- Embedded below ground
- Submerged zone
- Tidal zone
- Splash zone
- Atmospheric zone
Environments Encountered

MARINE EXPOSURE CONDITIONS

- Aerated Zone
- Splash Zone
- Tidal Zone
- Submerged Zone
- Sea Bed
- Splash Limit
- High Tide Limit
- Low Tide Limit
Marine Concrete Specification in Hong Kong
## Conventional Concrete Specification

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Design life</td>
<td>50 years</td>
<td>50 years</td>
<td>Not stated</td>
</tr>
<tr>
<td>Minimum compressive strength</td>
<td>45MPa</td>
<td>45MPa</td>
<td>40MPa</td>
</tr>
<tr>
<td>Maximum free water/cementitious ratio</td>
<td>0.4</td>
<td>0.42</td>
<td>BS6349 states 0.45</td>
</tr>
<tr>
<td>Minimum concrete cover for fully immersed, tidal, and splash zones</td>
<td>60mm nominal cover</td>
<td>60mm nominal cover</td>
<td>BS6349 states 50mm but preferred 75mm</td>
</tr>
<tr>
<td>Minimum concrete cover for aerated zone</td>
<td>60mm nominal cover</td>
<td>50mm nominal cover</td>
<td></td>
</tr>
<tr>
<td>Cement type</td>
<td>OPC; PFA (25-40%) replacement mandatory</td>
<td>OPC</td>
<td>SRPC not permitted. No codes specify PFA, GGBS, CSF</td>
</tr>
<tr>
<td>Range of cementitious content</td>
<td>360-430 kg/m³</td>
<td>375-550 kg/m³</td>
<td>350-400 kg/m³</td>
</tr>
<tr>
<td>Minimum slump</td>
<td>75mm</td>
<td>75mm</td>
<td>-</td>
</tr>
</tbody>
</table>
Durability of the Conventional Marine Concrete
3 Years Old Pier Structures
15 Years Old Pier Structures
17 Years Old Pier Structures
Chloride reaches threshold at cover of 60mm in 13 years.
Development of Marine Concrete Specification
Development of Marine Concrete Specification to Improve Durability

- In 1995, the PWD of CEDD instigated a consultancy to look into durability of its marine stock.
- CEDD’s Public Works Central Laboratory also carried out another series of research on the influence of microsilica on the strength and durability characteristic of concrete.
12 Trial Mixes for Laboratory and In-situ Test

• Laboratory Tests
  • Compressive Strength Test
  • Chloride Diffusion Test
  • Sorptivity Test

• Site exposure test for 3 months and 6 months
  • Chloride Diffusion Test
Durability Performance Tests

Results of Bulk Diffusion Test

Fig 3 - Mean Chloride Profiles of PFA Concretes at 84 Days

Mix Without Micro-silica (Mix A)
Mix With Micro-silica (Mix A/S)
<table>
<thead>
<tr>
<th>Mix</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cementitious Content (kg/m³)</td>
<td>428</td>
<td>430</td>
<td>419</td>
<td>437</td>
<td>418</td>
<td>438</td>
<td>420</td>
<td>418</td>
<td>419</td>
<td>417</td>
<td>418</td>
<td>419</td>
</tr>
<tr>
<td>Mineral Admixtures (kg/m³)</td>
<td>-</td>
<td>25% PFA</td>
<td>25% PFA</td>
<td>25% PFA</td>
<td>33% PFA</td>
<td>33% PFA</td>
<td>70% GGBS</td>
<td>70% GGBS</td>
<td>10% CSF</td>
<td>25% PFA &amp; 5% CSF</td>
<td>33% PFA &amp; 5% CSF</td>
<td>70% GGBS &amp; 5% CSF</td>
</tr>
<tr>
<td>Water/Cementitious Ratio</td>
<td>0.42</td>
<td>0.40</td>
<td>0.38</td>
<td>0.35</td>
<td>0.38</td>
<td>0.35</td>
<td>0.35</td>
<td>0.38</td>
<td>0.38</td>
<td>0.38</td>
<td>0.38</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Laboratory Test Results

| Compressive Strength (MPa) | 73 | 61 | 64 | 69 | 55 | 63 | 65 | 71 | 83 | 60 | 54 | 67 |
| Water Sorptivity (mm/min⁰.⁵) | 0.175 | 0.150 | 0.125 | 0.105 | 0.110 | 0.115 | 0.085 | 0.095 | 0.110 | 0.120 | 0.130 | 0.105 |
| Chloride Diffusion Coefficient (10⁻¹² m²/sec) | 3.25 | 5.10 | 5.15 | 3.60 | 3.35 | 6.20 | 2.10 | 1.75 | 2.75 | 4.50 | 4.50 | 1.40 |

Field Test Results (Chloride diffusion coefficient at tidal zone after exposure for)

| 3 Months (10⁻¹² m²/sec) | 4.2 | 6.1 | 4.4 | 3.9 | 5.8 | 4.7 | 2.7 | 2.8 | 2.7 | 4.6 | 4.3 | 2.0 |
| 6 Months (10⁻¹² m²/sec) | 3.2 | 3.1 | 3.1 | 1.9 | 2.4 | 2.5 | 1.6 | 1.4 | 2.5 | 3.0 | 2.6 | 1.8 |
Marine Concrete Specification, 1998
## Comparison of Different Concrete Specifications

<table>
<thead>
<tr>
<th>Country</th>
<th>Hong Kong</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design life</td>
<td>Not stated</td>
<td>50 years</td>
</tr>
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<td>Minimum compressive strength</td>
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## Comparison of Different Concrete Specifications

<table>
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<tr>
<th>Country</th>
<th>Hong Kong</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cement type</strong></td>
<td>CSF (5-10%); GGBS (60-75% for normal application and up to 90% for low heat application); PFA (25-40%), not to be used with GGBS</td>
<td>OPC; PFA (25-40%) replacement mandatory</td>
</tr>
<tr>
<td><strong>Range of cementitious content</strong></td>
<td>380-450 kg/m³</td>
<td>360-430 kg/m³</td>
</tr>
<tr>
<td><strong>Minimum slump</strong></td>
<td>75mm</td>
<td>75mm</td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td>Equivalent sodium oxide per m³ of concrete &lt; 3kg Flakiness Index &lt; 30% Elongation Index &lt; 35% Los Angeles Value ≤ 30% Sodium sulphate soundness weighted average loss &lt; 6%</td>
<td>-</td>
</tr>
</tbody>
</table>
Durability Performance of Marine Concrete
Projected chloride profiles of micro-silica concrete and conventional concrete at splash zone
Pictures of a 13 Years old Structures
Pictures of a 15 Years old Structures
Projected Chloride Profiles of Concrete at Different Exposure Periods

(C2) Pak Sha Wan Pier No.2 (NP149), 13.47, Splash (+2.96mCD), Pile Cap, Horizontal, 21/05/2015

- 5.0 years
- 10.0 years
- 15.0 years
- 20.0 years
- 25.0 years

Dc = 3.510 e-13 sq.m/s
Cs = 0.426 %

Corrosion Threshold Value = 0.06
Measures to Enhance Durability Performance
Projected chloride profiles of micro-silica concrete and conventional concrete at splash zone

Chloride content [%]

Distance from surface [mm]

Splash Zone

Conventional Concrete (11 yrs)

Marine Concrete (40 yrs)

Projected chloride profiles of micro-silica concrete and conventional concrete at splash zone.
Measures to Enhance Durability Performance

- Coating
  - Silane protection
  - Epoxy coating
Measures to Improve Durability

- Concrete Coatings
Measures to Enhance Durability Performance

- Coating
- Stainless Steel Rebars In Outer Layers
Measures to Improve Durability

- Reinforcement: Stainless Steel Bars

Source: International Molybdenum Association
Measures to Enhance Durability Performance

• Coating
• Stainless Steel Rebars In Outer Layers
• Rapid Chloride Penetration Test (CSI: Section 19)
Durability Performance Tests

Chloride Ion Penetration Test

CS1:2010 - Section 19 Determination of concrete’s ability to resist chloride ion penetration
## Chloride Ion Penetration Test

<table>
<thead>
<tr>
<th>Charge Passed (Coulombs)</th>
<th>Chloride Ion Penetrability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4000</td>
<td>High</td>
</tr>
<tr>
<td>2,000-4,000</td>
<td>Moderate</td>
</tr>
<tr>
<td>1,000-2,000</td>
<td>Low</td>
</tr>
<tr>
<td>100-1,000</td>
<td>Very Low</td>
</tr>
<tr>
<td>&lt;100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

Mean value shall be less than 1,000 coulombs after curing for 28 days
Part 2: Maintenance Strategies

- Maintenance Strategy for New Marine Structures
- Maintenance Strategy for Structures less than 10 years old
- Maintenance Strategy for Structures more than 10 years old
Maintenance Strategy for New Marine Structures

Aim:
To minimize the need of concrete repair during the 50 years design life of the structure
1. Strategy for New Marine Structures

Preventive Maintenance Strategy

1.1 Marine Concrete Specification
1. Strategy for New Marine Structures
   Preventive Maintenance Strategy

   1.1 Marine Concrete Specification
   1.2 Protective Coating
1. Strategy for New Marine Structures

Preventive Maintenance Strategy

1.1 Marine Concrete Specification

1.2 Protective Coating

1.3 Corrosion Monitoring
To monitor the ingress of chloride and
effectiveness of coating
CM Devices at Slab Soffit
Pak Sha Wan Public Pier
CM Devices at Pile Cap
Monitoring Box
Pak Sha Wan Public Pier
Fig. 1: Basic principle to determine the time-to-corrosion
2. Strategy for Structures < 10 Years Old

- 2.1 Assess the extent of chloride ingress
- 2.2 Protective Coating
Chloride Profile of Marine Structure After 3 Years of Exposure

(OPC concrete)

\[ Dc = 10.32 \times 10^{-13} \text{ m}^2/\text{s} \]

\[ Cs = 1.45\% \]
Chloride reaches threshold at cover of 60mm in 13 years.
3. Strategy for Structures
>10 Years Old

3.1 Install impressed current cathodic protection

 País de origen 30 years design life
 País de origen Stops further corrosion
3.2 Short term structural repairs
Prioritise repair by adopting a condition audit system
Example of a Condition Audit System

- Visual Inspection
Visual Inspection

- Carried out at low tide
- Photographic and video records
Example of a Condition Audit System

- Visual Inspection
- Database Assessment System
Condition Audit System

Defect Codes

For ease of defect identification, recording and future assessment
S: Spalling
S1: Spalling
S2: Spalling to Expose Reinforcement
C2: Cracks of Width < 1 mm
DLM: Delamination
## Standard Proforma for Visual Inspection

<table>
<thead>
<tr>
<th>Defects</th>
<th>Spalling/Delamin.</th>
<th>Crack</th>
<th>Rust</th>
<th>Other Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element Code</td>
<td>S1 (m²)</td>
<td>S2 (m²)</td>
<td>S3 (m²)</td>
<td>DLM (m²)</td>
</tr>
<tr>
<td>B/F4-G4</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/G1-H1</td>
<td>0.3</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/G2-H2</td>
<td>0.2</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C/G11</td>
<td>0.2</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C/G12</td>
<td>0.1</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C/G13</td>
<td></td>
<td>F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Database Assessment System

- Categorization of defects
- Calculation of frequency of defects for each category
- Deterioration index
- Deterioration ranking
Example of a Condition Audit System

- Visual Inspection
- Database Assessment System
- Detailed Investigation
Detailed Investigation

- Non-Destructive Tests
- Inspection Windows
- Cores for Compressive Strength Test
- Cores for Chloride Profile Test
3.3 Study the option of reconstruction
Conclusion

- Chloride ingress rate is substantially reduced by the adoption of the marine concrete specification.
- Results indicated that the durability of marine structures are greatly enhanced by the marine concrete specification.
- The service life will be further enhanced by the application of suitable concrete coating.
Conclusion

Maintenance strategies for marine structures could be based on concrete coating, cathodic protection technique and an effective structural condition audit system to prioritize concrete repair work.
End of Presentation

Thank you!