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Concrete Performance Based Infrastructure Asset Management
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- Director, Civil Works/ Structures, Steensen & Varming, Denmark 1979 - 1992
Contents

• Introduction to Marmaray and Oeresund Mega-Projects
• Oeresund versus Marmaray
• Concrete Strategy and Summary
• Some State of the Art Notes
• Lessons learned
• Status on the BC1 types of concrete
What is the Problem?

Ensure 100 years lifetime
Introduction

• Facts and figures, Oeresund
  – Design & Build
  – 1,200,000 m³ of concrete
  – Includes IMT tunnel, C&C and Bridge
  – Saline, aggressive environment
  – Water tightness
  – 100 years lifetime
  – Biggest IMT tunnel ever constructed
Each of the 175 m long tunnel elements weighs 50,000 t.
Cross section, Oeresund
Introduction

• Facts and figures, Marmaray
  – Design & Build
  – 1,300,000 m³ of concrete
  – Includes IMT tunnel, TBM tunnels
    C&C and NATM
  – Saline, aggressive environment
  – Water tightness
  – 100 years lifetime
  – Deepest IMT tunnel ever constructed
Introduction

• Facts and figures Immersed Tunnel, Oeresund
  – 20 elements, each 176x39x9 m
  – Max water depth 27 m
  – No external membrane
  – Approximately 100 kg reinforcement per m3
Reinforcement cage
The Railway tubes
Introduction

• Facts and figures Immersed Tunnel, Bosphorus
  – 11 elements each 135x16x8
  – Max water depth 58 m
  – External membrane mandatory
  – Approximately 280 kg reinforcement per m3
260 kg per m³!
Similarities

- Concrete is the dominating construction material
- Requirements to durability
- Destructive mechanisms
- Absolute Water tightness
- Conditions during hardening dictated by the material itself
Differences

- Construction methods
- Casting section principles
  - Full section 22 m length
  - Part section, full 135 m length
- Membrane principles
- Climate during casting of Concrete
- Physical support during casting of Concrete, (semi floating)
- Production Plant on site versus off-site
Semi Dry Dock, Marmaray
Semi Dry Dock, Marmaray
Yard, Oeresund, Reinforcement
Production Hall, Oeresund
Yard, Oeresund, Casting of 22 m sections
Production Hall, Oeresund
Yard, Oeresund, Other facilities

- Skidding beams
- Deep basin
- Aggregate pier
Yard, Oeresund, Other facilities
Yard, Oeresund
Strategy, both
Strategy

- The Employer defines and controls the Quality (min. requirements)
- Contractors must not compete on quality
- A sequence of controlled processes (ISO 9000/2000)
- Proven, well known technology
- Robust solutions
- 100 years lifetime without active protection systems
- As much freedom as possible
Controlled Processes
Summary of requirements

• Design and materials
  – First class constituents
  – Blast furnace cement, silica and fly-ash are all allowed
  – w/c \( \leq 0.40 \) and 0.45 respectively
  – Cover layer typically 50 or 75 mm depending on calculations
  – Extensive requirements to Quality Management and Conformity Procedures
Summary of requirements

- Pre-testing and Workmanship
  - Planning, planning and planning again
  - Quality Control Procedures
  - Comprehensive Pre-testing and Production-testing including correlation
  - Full Scale curing testing
  - Control of Early Age Cracking
  - Full Scale trial castings
Summary of requirements

• Ensuring Conformity of durability
  – Identify each important parameter
  – Identify direct, relevant and robust test methods
    • Long term but (more) reliable tests
    • Short term but less precise tests
    • Correlation between them
  – Integrate local knowledge and experience
  – Ensure traceability (90% upstream 100% downstream)
Frost Resistance
Temperature and Stress Requirements
Protection against evaporation
Conformity Procedures
Comparison of Concrete Requirements and Properties for other Structures
State of the Art Notes

- Chloride Penetration in Concrete
- Alkali-Silica Reactions
- Blast furnace Cement
- Casting Methods
- Crack Investigation
- Fire Resistance
Frost resistance

• Destruction Mechanisms
  – Internal damage
    • Critical dilation tests
    • Air void structure, specific surface and content
  – Salt Scaling of surface
    • Salt scaling tests

• Environment in Istanbul (not all of Turkey) and Scandinavia is different, yes – but?
Temperature and Stress

• Temperature simulations based on documented data
  – Acceptance criteria:
  – $D_{\text{ext}} < 15^\circ\text{C}$
  – $D_{\text{int}} < 15^\circ\text{C}$
  – Check against Delayed Ettringite Formations (DEF) if $T > 50^\circ\text{C}$
Temperature and Stress

- Stress simulations based on documented data
  - Crack risk < 0.7
  - Limiting temperatures must be established accordingly
  - Boundary conditions, creep and shrinkage during full hardening process
  - Curing
Temperature - Stress

Figure 2
Typical example of early-age stresses in part of the tunnel cross section

Temperature distribution at 80.00 hours
Conformity Procedures

- No.1: Product standards, ref. actual product standard
- No.2: 100% inspection
- No.3: Variables, Average Outgoing Quality Level (AOQL)
- No.4: Attributes, Acceptable Quality Level (AQL), ref. ISO 2859-1 191
- No.5: Attributes, Limiting Quality (LQ), ref. ISO 2859-2/101
- No.6 Rolling approval, AOQL
- No.7 Representative samples
Chloride Penetration

• Theoretical model:
  – Coefficient of diffusion (D)
  – Chloride Surface Concentration (C)
  – Works well in the laboratory
  – Poor correlation to accelerated tests and reality
  – Fortunately, a conservative model
Chloride Penetration

• Main features of protection:
  – Un-cracked Concrete (defects in mix and/or workmanship)
  – Impermeability (W/C ratio, correct aggregate corn-curve)
  – Chloride binding
  – Thickness of (Un-cracked) cover layer
Marine environment
Marine Environment
A-S Reactions (ASR)

- Upper limit to Na$_2$O-equivalent per m$^3$ of Concrete required
- Slow reactions can be difficult to detect
- Presence of fly-ash and blast-furnace is positive
- Risk for ASR is latent if external alkali sources are available (Sea-water)
A-S Reactions (ASR)

- Test methods
  - Slow test (52 weeks), concrete bars
  - Quick test (2 weeks), mortar bars
  - Petrographic testing

- Correlations required and/or recommended:
  - Between slow and quick tests
  - Quick test and Petrographic testing for slow reactions
Oeresund, construction
Filling of basin
## Recipe, comparison

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Oeresund</th>
<th>Bosph.1*</th>
<th>Bosph.2*</th>
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</thead>
<tbody>
<tr>
<td>P. Cement</td>
<td>324</td>
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<td>275</td>
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<tr>
<td>Slag Cement</td>
<td></td>
<td>375</td>
<td>-</td>
</tr>
<tr>
<td>Fly-ash</td>
<td>52</td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td>Micro Silica**</td>
<td>24</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>Water</td>
<td>123+12+8</td>
<td>140+3</td>
<td>111+15+3</td>
</tr>
</tbody>
</table>

* 1st and 2nd mix design  
** slurry, 50% Water
## Recipe, comparison

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<tr>
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<th>Oeresund</th>
<th>Bosph.1*</th>
<th>Bosph.2*</th>
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<tbody>
<tr>
<td>Fine Agg.0/2</td>
<td>633</td>
<td>462</td>
<td>640</td>
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<tr>
<td>Fine Agg.0/8</td>
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<td>Coarse Ag.2/8</td>
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<td>Coarse Ag.4/16</td>
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<td>Coarse Ag.8/22</td>
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<td>475</td>
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<td>Coarse Ag.16/25</td>
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## Recipe, summary

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Oeresund</th>
<th>Bosph.1*</th>
<th>Bosph.2*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder total</td>
<td>388</td>
<td>375</td>
<td>340</td>
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<tr>
<td>Aggregates total</td>
<td>1887</td>
<td>1830</td>
<td>1868</td>
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<tr>
<td>Additives (excl. w.)</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Chemical water</td>
<td>143</td>
<td>143</td>
<td>129</td>
</tr>
<tr>
<td>Density</td>
<td>2421</td>
<td>2351</td>
<td>2340</td>
</tr>
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</table>
Plants on Sites
Inside Railway Tunnel
Lessons learned
Oeresund

• Extended Employer’s Requirements were a success
• Only minor initial problems related to workmanship
• Placing and compaction methods must be in focus
• Reliable modeling of parameters can and must be done
Lessons learned
Oeresund

- Do not underestimate Pre-testing efforts (minimum 15 months)
- It pays off to do comprehensive testing to ensure suitable construction methods
- Addition of micro-silica improves parameters like workability, density, resistance against cloride
Lessons learned
Oeresund

• It is not easy to control amount of air (and therefore density) under site conditions

• Establishing a comprehensive database (>700 MB) was essential to organize and analyze data and experience
Lessons learned

Oeresund

• Heating during winter and cooling during summer of aggregates was necessary

• High capacity storage of aggregates was needed. 14 bins, each 1,500 tons capacity

• High capacity and skilled laboratory facilities on site needed
Lessons learned
Oeresund

• A precise adjustment of (different) setting times was essential for preventing early age cracking

• Control of fresh concrete temperatures was essential
Lessons learned
Oeresund

• Correlation between laboratory cubes and in situ drilled cores for frost resistance was very poor (non-conservative)
• Correlation of frost scaling tests were considerably more reliable after 42 cycles than after 28 cycles
Lessons learned
Oeresund

Figure 11
Relation between frost scaling at 28 and 56 cycles, single test results

Scaling at 56 cycles, kg/m²

Scaling at 28 cycles, kg/m²

\[ y = 3.1744 \quad x = -0.056 \]

\[ R^2 = 0.9123 \]
Considerable air loss from fresh concrete to hardened concrete was observed, average 3-4 %

Air loss after pumping was typically 0-2%

Compaction close to form => big air loss
Lessons learned

Oeresund

• No early age cracking occurred in the tunnel elements due to the casting method

• In ramps and portals very good correlation between calculations of cracking risk and temperatures were observed in reality
The Question is:

Can lessons be Confirmed from Marmaray

???

YES!
Lessons learned
Marmaray

• Slag cement with high slag content is vulnerable in relation to Early Age Cracking
• Long section casting of walls and roof slabs almost impossible
• Long section bottom slab is possible (135 meter)
• Max section length walls ~ 20 – 25 meter
Thank you for listening

Questions & Answers