Introduction of Revised Specification for Shotcrete and Other Shotcrete Development

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Service life prediction of shotcrete

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Background of research work

• In recent decades, economical and environmental changes have greatly influenced the construction industry
  – Today, owners and specifiers ask for strong, green and durable materials, and they need to know how long they can expect the performance to remain acceptable

• This has brought the concept of service life prediction

Background of research work

• Concrete community adapted to these new challenges
  – Performance based specification
  – Predictive models

• While important data has been generated for regular concrete, very little information is available on the service life of shotcrete specifically

Background of research work

• Shotcrete is not regular concrete
  – Boiled water absorption and volume of permeable voids are higher than that generally found for similar concrete
  – Compaction and mixing energy is significantly different compared to cast-in-place concrete
  – However...

• Shotcrete is generally reported as having excellent durability
Background of research work

- Specification often calls for a maximum value of absorption for shotcrete (ASTM C642)
  - Which is the source of animated discussion both around the construction site and technical committee meetings!

The industry now often relies on the boiled water absorption (BWA) to estimate the durability of shotcrete [Morgan et al., 1987]


Background of research work

- Researchers know that contaminants ingress in the concrete porosity through different transport mechanisms
  - Permeability
  - Moisture diffusivity
  - Ionic diffusivity
  - Capillary Absorption
- Every mechanism refers to a distinct physical phenomenon
- The environmental exposure should be considered to decide which test is relevant

<table>
<thead>
<tr>
<th>Sprayed Concrete Quality</th>
<th>Permeable Void Volume (%)</th>
<th>Boiled Absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>&lt; 14</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>Good</td>
<td>14 – 17</td>
<td>6 – 8</td>
</tr>
<tr>
<td>Fair</td>
<td>17 – 19</td>
<td>8 – 9</td>
</tr>
<tr>
<td>Marginal</td>
<td>&gt; 19</td>
<td>&gt; 9</td>
</tr>
</tbody>
</table>

[Source: Morgan et al., 1987]

Objectives

- Generate data on shotcrete transport properties
  - And compare them to regular cast in-place concrete
- Offer guidelines for engineers to help them specify relevant material information
  - Apart from compressive strength, what else should we be controlling shotcrete quality for:
    - Boiled water absorption?
    - Rapid chloride permeability test?

Specific Objectives

- Phase 1 (2007-2009) - Exploration
  - Perform a complete characterization of several conventionally placed and sprayed concrete mixtures
  - Explore the relationships between BWA and …
    - mixture design?
    - shooting parameters?
    - RCPT?
  - Generate preliminary data on STADIUM software for service life prediction

Based on results from Phase 1…

- Phase 2 (2011-2013)
  - Perform a complete characterization of more focused mixture selection
  - Confirm (or invalidate) data from phase 1
  - Perform refined analyses using a service life prediction software
In Phase 1, several shotcrete mixtures were placed and characterized in Laval University's shotcrete laboratory. The main element studied was the relevance of specifying BWA test as a durability criterion. To achieve this objective, BWA results were compared to RCPT results…

### Phase 1 - Results

![Graph showing BWA vs. Capillary Absorption](image)

### Durability?

- From previously exposed information, it appears that BWA poorly correlates with RCPT.
- Also, it must be emphasized that RCPT does not help owners and engineers to estimate the service life of their concrete infrastructures…
- The next step in our investigation was therefore to answer the following question:

  *How can we predict shotcrete service life?*

### Service life prediction

- Numerous models are available to predict the service life concrete infrastructures.
- There is an increasing trend in the industry to include service life requirements in specifications:
  - Contract documents can contain clauses such as: *concrete shall have a service life of … years*
    - Panama Canal
    - Multilevel parking structures
    - DOT rehabilitation projects
  - …

However, very little information has been published on this subject regarding shotcrete… and the problem was addressed in this project:

- Tests were performed on several shotcrete mixtures:
  - Migration test (ASTM C1202 modified)
  - BWA (ASTM C642)
  - Drying test
  - Pore solution extraction
- Service life modeling was performed with STADIUM ® software1 on tested mixtures.

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1 Developed by SIMCO TECHNOLOGIES
STADIUM® software

- STADIUM® is a numeric tool that predicts the ingress of corrosive species in cementitious materials
- Inputs required to perform service life simulations...
  - Test results
  - Material properties
  - Environmental exposure
- Inputs are computed in a multi-ionic model that considers
  - Mass and energy transport equations
  - Chemical equilibrium equations

Service Life Prediction

- Simulation example (STADIUM®)

Service Life Prediction

- Comparison of 4 mixtures
  1. Control (SUMMA): W/Cm=0.45 – Type GU+8% SF
  2. Dry-mix shotcrete: W/Cm=0.51 – Type GU+10% SF
  3. Wet-mix shotcrete: W/Cm=0.40 – Type GU+8% SF
  4. Dry-mix mortar: W/Cm=0.47 – Type GU+12% SF

Service Life Prediction

Phase 2 - Current project

Based on results from Phase 1, a new experimental campaign was launched to further investigate the durability and service life assessment of shotcrete
Phase 2 - Methodology

• Shotcrete mix designs

<table>
<thead>
<tr>
<th>Mix 1</th>
<th>D-M1</th>
<th>X</th>
<th>X</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix 2</td>
<td>D-M2</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mix 3</td>
<td>W-M3</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mix 4</td>
<td>D-M4</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mix 5</td>
<td>W-M5</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mix 6</td>
<td>D-M6</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mix 7</td>
<td>W-M7</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mix 8</td>
<td>W-control</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

- OPC
- FA
- ACW
- ACNB
- Silica fume
- Ternary
- Control

Phase 2 - Methodology

• Selected shooting parameter
  - Identical shooting energy

1m (3'4'')
200 CFM

Phase 2 - Methodology

• Batching process

3 x

Phase 2 - Methodology

• Testing program

3 x

- Standardized tests
  - ASTM C1604 and C39
  - ASTM C642 (BWA)
  - ASTM C1202 (RCPT)

- Tests required for STADIUM ® analysis
  - Migration test (C1202 modified)
  - Drying test
  - Pore solution extraction

- Other
  - Imagery analysis

Preliminary results

Compression Test Results (28d) ASTM C1604 and C39

- Data showing Compression Test Results
Preliminary results

Boiled Water Absorption (S66) ASTM C642

- Quality instructions (OCP, OPC, OPC+SP, OPC+SF)
- Migration, drying test, pore solution extraction

Summary

- Standardized tests presented above useful for quality control
  - Relatively cheap
  - Quick results
- However, they do not allow for a reliable service life estimation
- Adapted tests are required for such an assessment
  - Migration, drying test, pore solution extraction

The results from this study aim at providing
- A basis for comparison between CIP concrete and shotcrete performance
- A better understanding of the transport properties in shotcrete
- The groundwork for development of new shotcrete performance specifications

Future work

- Finish experimental phase

- Analyse shot and batched mixes using STADIUM®
- Vary exposure conditions
  - Marine infrastructure
    - Saline environment
    - From piles to top deck
  - Road infrastructure
    - De-icer salt
- Estimate service life
  - Compare mixes from project results
  - Compare mixes from SUMMA results
Thank you

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