Emerging Technologies

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Shotcrete R&D

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Industrial Chair - History

• In the late 80’s, the MTQ was actively looking at shotcrete as a repair methods for its structures
  – It had a limited success, and realized some R&D was needed to solve a few issues (e.g. cracking, durability)
  – A few M.Sc. projects were undertaken
• In 1991, it became clear that shotcrete was there to stay, and a more organized research effort was envisioned: an Industrial Chair was put together

Industrial Chair - History

NSERC Industrial Chair on Shotcrete and Concrete Repairs (1994-2004)
NSERC Industrial Chair on Durable Repair and Optimized Maintenance of Concrete Infrastructures (2006-2011)

Shotcrete

• Early on, shotcrete raised many questions on:
  – Mix design performances (durability, mechanical properties and bonding)
  – Placement techniques (f(mix design)).
  – Jobsite and long term results
• Objective: develop knowledge to increase the confidence of the user and increase use in general of shotcrete
Mixture design

- Accelerators (dry and wet-mix)
- Air entraining admixtures
- Shrinkage reducing admixtures
- Internal curing agents
- Supplementary materials et replacements
  - Fly ash
  - Ternary binders

Set accelerators in dry-mix shotcrete

Recommendations

- In dry-mix shotcrete, the chemical family of a set accelerator is the main selection criterion
  - Aluminates based powders are the only one recommended for repairs exposed to aggressive environments
  - Carbonate based are especially efficient in the mining environment, where short term properties are very important

Set accelerators ...

Setting time (dry-mix)

Compressive str. (dry-mix)

Deicer salt scaling (dry-mix)
Air entraining admixtures

Objectives
- Confirm the positive effect of AEA on frost durability in dry-mix shotcrete
- Study the option of using AEA in the powder form
  - Better control in pre-bagged material

Deicer salt scaling (dry-mix)

![Graph showing material loss with and without AEA](image)

- Mix 1
- Mix 2
- Mix 3 (Plain)

Powdered AEA

Air entraining admixtures

Results & Observations
- Necessity of AEA in dry-mix shotcrete exposed to freezing environments is confirmed
- Powdered AEA are equivalent if not better:
  - Spacing factor usually below 200 µm
  - Dosage (by mass) << 1% of binder by mass

Placement methods

- High initial air content concept
- Shooting consistency
- Nozzlemen certification
- Reinforcement encapsulation
- Multi-layer application

High initial air content concept

Objectives
- Use air bubbles to improve workability of the fresh concrete (good pumpability) while generating a “slump killer” effect during compaction of the material by pushing out the air bubbles, thus creating a stiffer material (good shootability)
- Confirm the usability of the concept on a job site
High initial air content concept

Results & Observations
- The concept is applicable on regular job sites (and has been for 15 years in many areas)
- In-place air content is always sufficiently low to promote good compressive strength
- In-place spacing factor extremely good, typically < 200 µm
- Helps avoid set accelerators in “normal” placing conditions
Recommendation: Use it!

Rebar pull-out test

Average rebar pull-out strength

Nozzlemen certification
- Nozzlemen certification program created in 1997 for Quebec DOT
- Strong implication from the Industrial chair on the ACI shotcrete nozzlemen certification program
- ACI “Shotcrete Nozzlemen Certification” available since 2001
- Adopted by Quebec DOT in 2002

Recent years R&D
- Inform and capture your interest in shotcrete research!
  - Our lab…
    - …or the dustiest lab in North America
  - Pumping…
    - … why a pizza is a good comparison
  - Durability and service life…
    - … of course it’s as good as cast in-place!
  - Ultra High Early Strength
    - 10 MPa in minutes…
  - Placement…
    - … particles flying at 500 km, I swear!
Continuous Rebound Measurement

Service Life of Shotcrete

Background

• Shotcrete shows more voids than regular concrete
  – Absorption values and volume of permeable voids are higher than that generally found for similar concrete
  – however...

• Shotcrete is generally reported as having an excellent durability

Background

• 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!

<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>

[Morgan et al., 1987]
Challenge & Objective

- Predict long term durability of various types of shotcrete
  - Placement process changes the in-place composition and has an impact on the consolidation level
- Generate data on shotcrete transport properties
  - And compare them to regular cast-in-place concrete!

Transport

- Water permeability
  - Pressure
- Water diffusion
  - RH
- Ionic diffusion
  - Concentration
- Capillary absorption
  - Surface tension

Service Life Prediction

- Chloride concentration @ 25 mm depth
- Time (year)

Service Life Prediction

Discussion

- Mix design plays an important role
- The shotcrete placement method is creating a very unique and special type of concrete!

Placement of shotcrete

Contributors: Nicolas GINOUSE
Benoit BISSONNETTE
Background

• Study of particles transport

Shotcrete cinematic

Background

• A wide range of particle velocities are reported in literature
  - Stewart (1933)
    220-330 mph (Gunite)
  - Austin and Robins (1995)
    65-135 mph (dry-mix)
    25-65 mph (wet-mix)
  - Armelin high-speed filming (1997)
    11-60 mph

• No characterization of the entire flow of particle out of the nozzle
### Objective & Methodology

- **Study Rebound** (through Armelin’s model 1997)

  ![Impact model](image)

  Particle tracking during the impact

  ⇒ Verify and enhance rebound model accuracy

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### Discussion

- **Perspective of this study**
  - Effect of equipment on material exit velocities, velocity profiles and energy profiles
    - Understanding and describing the flow of material
  - Effect of material flow characteristics on:
    - rebound
    - in-place compaction and composition
    - in-place mechanical properties
    - durability

### Concluding remarks

- Research in shotcrete is strong!

- Many subjects are of interest:
  - pumping, placement, durability, etc.

- Look for it!

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### Special thanks...

- This type of research requires strong support from the industry

- **Contributors**
Thank you!

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You may want to visit www.shotcrete.org!