Shotcrete and Waterproofing for Operational Tunnels

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Animateur

International Tunnelling Association

Working Group on Shotcrete Use
Basilica Cistern
Istanbul, 6th Century
The Basilica Cistern
Istanbul, 6th Century

THE BASILICA CISTERN

Constructed in the 6th century during the reign of Emperor Justinianus, the most prosperous period of the East Roman Empire, the cistern Basilica is 70m. in width and 140m. in length. The dome, covering an area of 9800 m², is supported by 336 marble columns arranged in 12 rows each consisting of 28 columns placed at a distance of 4m 90cm. from one another. The capitals of these 9 m. high columns are a blend of the Ionic and corinthian styles with a few exceptions which are in the doric style and not ornamented. The cistern is surrounded by a 4 m. thick wall of brick and the mortar used in constructions is very special and water-proof. The water reserved in the cistern was transported from the Belgrad forest which is 19 km. from the city.

In 1985 the Metropolitan municipality of Istanbul undertook the restoration of the cistern. On the 9th of September 1987, it was opened for visitors as a vitalized example of universal cultural heritage.
ITA Activities on Waterproofing

- WG 6 – Maintenance and Repair
- Wg 12 – Shotcrete Use
INTERNATIONALE ERFahrung IN DER TUNNELABDICHTUNG

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Waterproofing Requirements

- More sophisticated equipment underground
- More demanding public
- Psychological aspects of leakages
- Improvement of waterproofing techniques

On the other hand
- Increasing costs
- No general solution: functionality, durability, environment
Different Criteria for infiltration

<table>
<thead>
<tr>
<th>Location</th>
<th>Infiltration Rate</th>
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<tbody>
<tr>
<td>Alp Transit</td>
<td>0.13 l/m².day</td>
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<tr>
<td>Sweden</td>
<td>1.1 l/min.100m</td>
</tr>
<tr>
<td>Norway (highway)</td>
<td>14 l/min.km</td>
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<tr>
<td>São Paulo Subway</td>
<td>1.0 l/min.km</td>
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</tbody>
</table>
Underground Railway Systems
\( l/m^2 \cdot \text{day} \) (Haack, 1991)

<table>
<thead>
<tr>
<th>City</th>
<th>Short</th>
<th>Long</th>
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<tbody>
<tr>
<td>Washington, D.C.</td>
<td>10.7</td>
<td>0.9</td>
</tr>
<tr>
<td>San Francisco</td>
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<td></td>
</tr>
<tr>
<td>Atlanta</td>
<td>0.9</td>
<td></td>
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<tr>
<td>Boston</td>
<td>1.8</td>
<td></td>
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<tr>
<td>Baltimore</td>
<td>5.3</td>
<td>0.7</td>
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<tr>
<td>Buffalo</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Melbourne</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>Antwerp</td>
<td>0.25</td>
<td>0.1</td>
</tr>
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</table>
Norwegian Subsea Bored Tunnels
WATER CONTROL

1) PROBE DRILLING

2) PRE-GROUTING

GROUTING PRESSURE UP TO 10 MPa

PRESET QUANTITY FOR ECONOMICAL PUMPING: ~300 l/min per km

ACHIEVED AT OPENING: 20-460 l/min per km
Stop Criteria for Cement Grouting

(Gustafson & Stille, 2005)
Norwegian Operational Experience (ITA Open Session, 2005)

- Water ingress reduced by up to 50% (self-healing)
- Algae growth in some tunnels
- Periodical replacement of installations
- Yearly maintenance cost: 1 - 1.5% of investment
- Investment: US$ 6,000.00 – 10,000.00 (2- or 3-lane tunnels)
Damaging Effects of Water on Tunnels (ITA WG 6)

17 types of defects and remedial measures

- Corrosion of internal fittings
- Frost damage
- Erosion of mortar
- Corrosion of reinforcement
- Degradation of concrete
- Swelling soil
- etc

(chemically aggressive water)
Water Inflow x Durability

- Flow rate
- Chemical aggressivity

Ex:
- Kanmon Strait Tunnels
  (concrete, sea water; Miyaguchi, 1986)
- Cast iron segmental lining
Shotcrete for Final Lining

- Material requirements
- Less material
- Concept of rock reinforcement vs rock support
- “design attitude”
“The contributions from different countries illustrate well the widely different views on rock support design. This becomes especially evident when comparing sometimes the over-conservative cast in place concrete linings with what evidently is satisfactory support under similar conditions using shotcrete. There are many examples of thickness reduction from one meter down to 10 to 15 cm of shotcrete.”

K. Garshol
Paulo Afonso IV

Concreto:
Espessura de 1 a 1,8 m

34 m
Paulo Afonso IV
Re et al. (1982)

Shotcrete: 10 to 15 cm thickness
USINA DE PAULO AFONSO III
USINA DE PAULO AFONSO IV
### Single shell lining in Germany

Single-track tunnels (Pöttler & Klapperich, 2001)

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<tr>
<td>Ground</td>
<td>S/M</td>
<td>S/M</td>
<td>M</td>
<td>C</td>
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<td>Pressure (bar)</td>
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<td>0.6</td>
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<td>Thickness (cm)</td>
<td>37</td>
<td>25</td>
<td>39</td>
<td>40</td>
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<tr>
<td>Ground</td>
<td>C</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>G/M</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>0.6</td>
<td>0</td>
<td>1.2</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Thickness (cm)</td>
<td>25</td>
<td>40</td>
<td>55</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>

C - claystone
M - marl
S - sandstone
Comments by Pöttler & Klapperich, 2001

- 10 - 15% savings due to single shell concept

- Scattered considerations about load on the second layer: full load to partial load

- Different design philosophy → even more significant savings
Single shell lining in São Paulo

Single track tunnels

Year: since 1981

Ground: stiff clay with water-bearing sand layers

Pressure: 0.5 to 2.0 bar

Total thickness: 20 to 25 cm
Shotcrete lining for the São Paulo Subway

- $t = 0.25 \text{ m}$, $p = 2 \text{ bar}$
- $t = 0.40 \text{ m}$, $p = 0.7 \text{ bar}$
- $t = 0.25 \text{ m}$, $p = 0.5 \text{ bar}$
Opinions from National Groups

- Conflicting opinions
- Different technical cultures
- Role of information exchange
- Technology property
1988 ITA Congress on Tunnels and Water

Schryer (Germay): shotcrete shells not suitable for zones more than 10m below water

Astad & Heimli (Norway): shotcrete considered watertight for practical purposes

Current shotcrete technology: low hydration
heal cement, additives for low porosity:
$k \sim 10^{-14} \text{m/s}$
\[ r_{eq} = r_e \left( \frac{r_e}{r_i} \right)^{-k_g/k_1} \]
Approximate expression for lining permeability

\[ Q = 2\pi k g h \left\{ 1 - 3 \left( \frac{r_{eq}}{2h} \right)^2 \right\} \frac{1}{\left[ 1 - \left( \frac{r_{eq}}{2h} \right)^2 \right]^2} \ln \frac{2h}{r_{eq}} - \left( \frac{r_{eq}}{2h} \right)^2 \]
ZUQUIM TUNNELS
Permeability lining (m/sec)

São Paulo Leste
Sarnia
Battery
Hudson PRR Hudson River
Blackwall (2)
Clyde
Greenwich
Toronto
Rotherwhite
Maria Maluf A-I
Maria Maluf I-A
Santa Cecilia
Sevem
Estacionamento
Luminarias

○ Shotcrete
■ Bolted cast iron with concrete
□ Bolted cast iron
▼ Bolted concrete
Drained Tunnels
Overview of Waterproofing Techniques: Drainage

Lemke et al., 2005
Cost of drained and watertight tunnel
(Stans/Terfens Tunnel, Insam et al., 2005)
The End