Sprayed concrete linings waterproofed with bonded membranes

- Physical and mechanical properties – the key to permanent function and durability

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Stakeholders in this project

Supplier industry of membrane and concrete technology for tunnel linings:
- BASF Construction Chemicals Europe AG
- Orica International Ltd

Public traffic administrations
- Norwegian National Rail Administration
- Norwegian Public Roads Administration

University and research institutions
- Norwegian University of Science and Technology
- SINTEF Building and Infrastructure

Other:
- Norwegian Tunnelling Society NFF
Main scope of project:
- Investigations of the properties of sprayed concrete tunnel linings waterproofed with bonded membranes
- Emphasis on the real in-situ boundary conditions
- Physical and mechanical properties of the sprayed concrete and membrane materials
- Verify system function of the lining structure
- Evaluation of possible degrading processes and durability of the lining system
Main boundary conditions for the tunnel lining

Rock mass
- Geomechanical loads

Groundwater
- Hydraulic loads
- Exposure to geochemistry

Tunnel climate
- Temperature and humidity in the tunnel air
- Possible freezing
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**Tunnel climate**
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Boundary condition groundwater:

Design options for tunnel linings
- Fully tanked (undrained) waterproof
- Drained lining structure, no waterproofing in invert

*Completely drained waterproof lining
*Undrained waterproof lining in whole perimeter*
Boundary condition groundwater:

Design option for SCL in hard rock
- Partially drained tunnel structure, no waterproofing in invert

Undrained waterproofing in walls and crown

Excavation damaged zone EDZ
Bonded waterproof lining structure - main processes

Liquid water saturates cracks and interface imperfections in the concrete.

Liquid water is STATIC in the lining structure.

Water vapor migrates through the lining.
This observation can be explained by moisture transport mechanisms, in which capillary and vapor transport are dominating. The principles for such moisture transport mechanisms are commonly known in the field of building physics.
Hydraulic conductivity (water permeability):

Sprayed concrete:
Hydraulic conductivity : < 10^{-14} m/s  
Capillary porosity : 18-20 %  
Macro porosity : 4-6%  

Intact sprayed concrete material is literally impermeable

Water vapor permeability:

Sprayed concrete and the tested EVA based membranes exhibit similar water vapor permeabilities
Hygroscopicity (water retaining property) of sprayed concrete and membrane materials
How much water can the two materials contain at a certain relative humidity?
Hygroscopicity (water retaining property) of sprayed concrete and membrane materials

How much water can the two materials contain at a certain relative humidity?

1. Immersion, complete saturation
2. In-situ tunnel lining at membrane location, **Tensile strength: 1.1 - 1.5 MPa**
3. Standard laboratory conditions, **Tensile strength: 2-3 MPa**
4. Range of humidity in membrane material exposed to tunnel construction ventilation, **Tensile strength: 2 – 10 MPa (!!!)**
Bottomline:
Physical properties and the practical consequences

In a continuously bonded lining structure:

What does the membrane do to the concrete?
What does the concrete do to the membrane?
What does the membrane do to the concrete?
- Prevents liquid water on cracks to flow through the lining
- \[\Rightarrow\] Keeps liquid water *static* in the concrete
- Allows water vapor to migrate through the lining
- \[\Rightarrow\] Keeps the concrete partially saturated (avoids complete saturation of the concrete)

What does the concrete do to the membrane?
- Due to the capillary pore structure of the concrete, the membrane will only be exposed to water vapor with a certain relative humidity at the membrane/concrete interfaces
- The higher hygroscopicity of the concrete will keep the moisture content in the membrane relatively low
- Shrinkage and thermally induced deformations will expose the membrane to elongation across the cracks in the concrete at the membrane/concrete interfaces
Singapore – 11 November 2016

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Importance of vapor permeability – vapor permeable membrane

Degree of saturation of concrete across lining

Waterproof AND vapor permeable membrane.

DCS [%]

ROCK MASS

MEMBRANE

SPRAYED CONCRETE
Importance of vapor permeability – vapor proof membrane

Vapor and water proof membrane. The membrane poses a barrier to vapor transport, saturation of concrete on the «rock side» of the membrane possible.
Durability considerations

- Migration of water vapor $\Rightarrow$ partially saturated concrete material on the «rock side» of the membrane
- An unsaturated concrete cannot transmit hydraulic pressure in the pore-structure
- Pore water pressure in the concrete is therefore very unlikely
- Water in the lining structure is static. Leaching of the concrete and constant feeding of aggressive ions will not take place
- The relatively low degree of saturation in the concrete prevents freezing damage
- The low degree of saturation of the concrete provides favorable moisture condition for the membrane, which explains the high measured in-situ values for tensile bonding strength
Testing of concrete and membranes: Some important findings

In-situ tensile bonding strength of membrane: 1.1 -1.5 MPa
50 freeze/thaw cycles to -3 °C at the membrane (corresponding to approx -7 °C in the tunnel air) gave no significant reduction of tensile bonding strength

Bridging of cracks up to 4 mm crack width (at 3 mm membrane thickness) is possible at 20 °C
Temperature sensitive: at temperatures in the range of 0 to -3°C bridging of cracks up to 1 mm crack width is possible

Shear deformability up to approximately 1 mm without initial rupture

Measured sprayed concrete material parameters:
Uniaxial compressive strength : 65 – 80 MPa
Young’s modulus: 25-30 GPa
Energy absorption: 900-1000J (E-class 1000)
Water permeability : extremely low, <10^{-14} m/s (intact material)
Vapor permeability : high
Capillary porosity: 18-20%
Macro porosity: 4-6 %
Implementation of research results

- The Holmestrand rail tunnel, south Norway. Lining constructed June-October 2014.
- Final lining with SCL and spray-applied membrane was successfully used: waterproof, vapor permeable and frost resistant, implementing research results
- The lining system SCL with spray applied membrane was included in the Norwegian National Rail Administration’s standards as an approved method as of January 2016
Main areas of further work - outlook

- Further develop the sprayed concrete material for permanent lining purposes
  - Crack width control/reduction: Increased ductility of the concrete
  - Fiber types and dosages to distribute cracks and reduce crack widths to the capillary size range
- Increase the quality of the sprayed concrete application process, with increased consistent compaction of the concrete on the rock wall, in order to get a more homogenous concrete material
- Membrane: Improve the constructability details of the membrane application process
THANK YOU FOR YOUR ATTENTION

Gevingås rail tunnel, April 2016