Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

New development of sprayed concrete with improved waterproofing, durability and sustainability performance

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ABSTRACT: Sprayed concrete in combination with rock bolts is successfully being used for permanent rock support in tunnels. The main shortcoming is that sprayed concrete alone is unable to function as the permanent waterproofing with strict requirements on a dry interior tunnel surface. Final linings with precast or cast-in-place concrete with sheet membrane waterproofing represent an excessive structural design in hard rock conditions. The SUPERCON research project (Sprayed sUstainable PErmanent Robotized CONcrete) is currently aiming to improve the sprayed concrete technology to enable a permanent waterproof tunnel lining, based entirely on sprayed concrete.

Laboratory and full scale spray application testing include innovative mix designs with significantly reduced cement content. The effects of the use of fly ash and limestone powder binder replacement, hydration accelerators and high-performance shrinkage reducing agents as well as adding of polymer modification to the concrete mix and special steel fibres for the distribution of cracks in the hardened concrete were studied. A significant reduction of the autogenous shrinkage potential, and a reduction in the water transport (capillary suction and permeation) through cracks in the concrete using polymeric modification of the concrete was achieved. The use of shrinkage reducing measures in the mix, combined with anti-dryout measures on the sprayed concrete surface significantly reduce cracking risk. The research results so far indicate the feasibility of a waterproof sprayed concrete without a waterproofing membrane.

1 INTRODUCTION

Sprayed concrete for has been successfully used for permanent rock support in hard rock for several decades in Scandinavia. The final inner lining for waterproofing and aesthetic purposes has been formed from cast in-place or precast concrete in many cases. Several projects have been successfully completed with the lining system based on sprayed concrete and spray applied waterproofing membrane in a continuously bonded structure. However, several technical challenges related to the construction and application process have yet to be improved, to make this method a robust method for tunnel applications. The SUPERCON project aims to resolve the shortcomings which currently disqualify sprayed concrete for use as the final inner lining. The main material improvements of the concrete are described together with the most important findings.

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1.1 *Current practice*

In jointed hard rock, a rock support lining based on a combination of fibre reinforced sprayed concrete and fully grouted rock bolts has proved to be a functional and durable technical solution for decades. Monitoring of loads in the lining suggest the that loads are mainly local and related to instable blocks or rock with poor quality which occurs in only a portion of the tunnel contour (Grimstad et al. 2015, Holter, 2015).

From 2020 the minimum required thickness for sprayed concrete in Norwegian traffic tunnels (rail and road) has been 80 mm, while for subsea road tunnels with exposure to saline groundwater in a drained design concept with water management based on pre-grouting, the minimum required thickness is 100 mm. In zones of weaker or more jointed rock, sprayed concrete thicknesses of up to 250 – 300 mm can be applied. Sprayed concrete linings should provide both immediate and permanent ground support. The material properties should provide sufficient support in hard rock and weakness zones, and provide long term durability under exposure to geomechanical, hydrogeological and geochemical conditions for the design service lifetime of the project. Recent research (Holter, 2015) has also demonstrated that the intact sprayed concrete material, when constructed according to strict material requirements (Norwegian Concrete Association, 2011), has an extremely low permeability and is literally impermeable from a practical perspective. Traffic tunnels in hard rock have traditionally been constructed with a permanent rock reinforcement lining and a separate inner water drip and frost protection structure. This structure acts as a drainage shield and leads seeping water to the invert, hence protecting the carriageway from drips (Broch et al. 2002). To manage the water ingress to the tunnel as well as the effects on the groundwater, a pre-grouting program is always part of this method. The tunnel structure will be permanently drained, as illustrated in Figure 1.

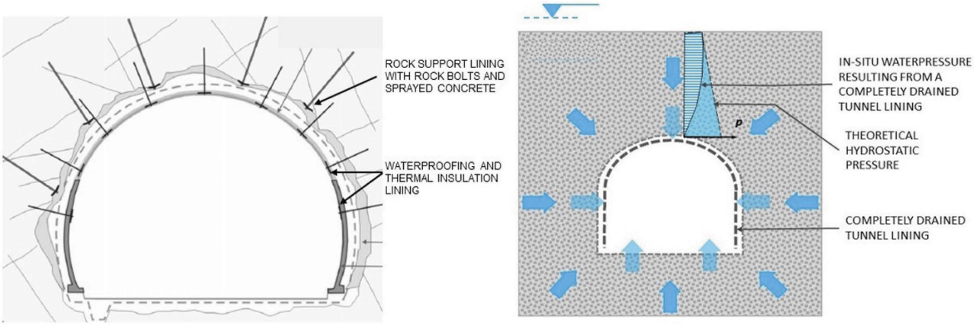


Figure 1. Diagrams of drained tunnel lining systems in a rock tunnel in Scandinavian practice. Left: The layout of the lining system (after Broch et al. 2002). Right: The groundwater pressure around a completely drained tunnel.

The tunnel lining system based on sprayed concrete and bonded waterproofing membrane has been used more recently for projects in Norway and is illustrated in Figure 2. This lining system contains three significant innovations: the bonded membrane and hence the undrained waterproofing function of the lining structure, the design as a partially drained tunnel with the effect of the increased hydraulic transmissivity of the excavation damaged zone (EDZ), and the freeze thaw resistance of continuous structure based on sprayed concrete, without any thermally insulating layers. These issues have been addressed in several research projects. The drainage effect of the EDZ has been investigated in three different research works (Holter 2014, Holter 2015, Nilsen 2019 and Aas 2020) within hydrostatic pressures up to approximately 0,5 MPa in jointed hard rock. The freeze-thaw resistance was investigated in a laboratory and field study for Norwegian railroad tunnels (Holter et al. 2016). The constructability of the lining system based on bonded membrane and sprayed concrete contains several challenges which relate to workmanship, quality control, handling of drips and moist

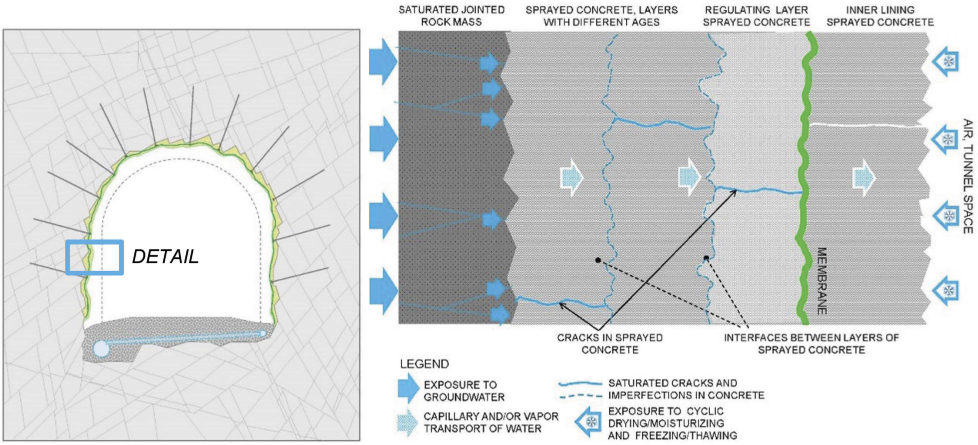


Figure 2. Diagrams of a partially drained tunnel with spray-applied bonded membrane, with a detailed section of lining with sequence of material layers from the rock surface to the tunnel space.

conditions, and construction risk. The need for a more robust technical solution with less sensitive details regarding construction has been a driving factor for developing a waterproof sprayed concrete.

1.2 *Layout of technical solution with waterproof sprayed concrete*

The development of a waterproof sprayed concrete lining is based on a layout which uses the established rock support practice with rock reinforcement based on sprayed concrete and rock bolts. The final waterproofing lining is added as separate bonded applied onto the rock support surface. The conceptual layout with waterproof sprayed concrete is a further development of the undrained and waterproof lining with bonded membrane and is illustrated in Figure 3. The waterproof sprayed concrete will act as a waterproof but vapor permeable layer which is applied on the surface of the rock reinforcement sprayed concrete. The rock reinforcement lining is assumed to be designed for all geomechanical loads, and hence to be

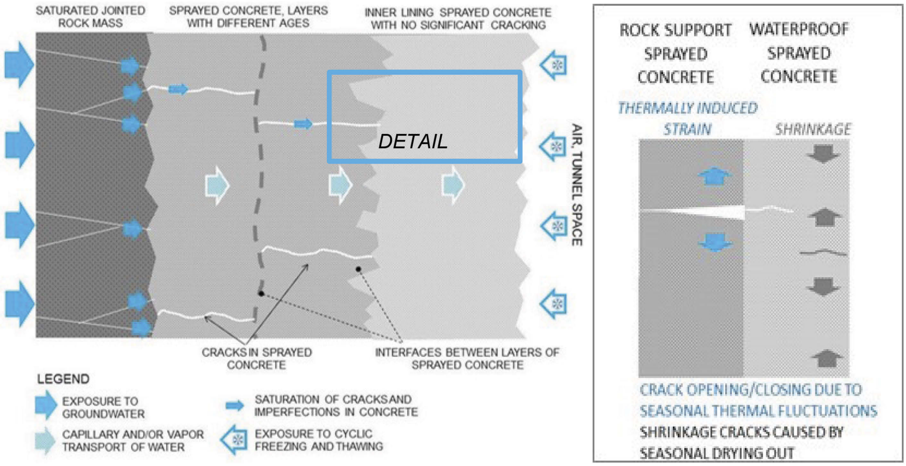


Figure 3. Principal sketches illustrating the layout and function of a lining structure with waterproof sprayed concrete. Left: Lining section with the rock support and waterproofing layer. Right: Detailed section of interface between rock support sprayed concrete and the waterproof sprayed concrete.

stable. The inner waterproof sprayed concrete will therefore be designed to resist cracking and the thickness needs to consider the effects of seasonal moistening and drying out, as well as freeze-thaw cycles. The material development process for the waterproof sprayed concrete in the SUPERCON research project has addressed shrinkage cracking and functional waterproof performance during application as main technical goals.

2 EXECUTED WORK

The experimental work was focused on addressing the cracking problem of sprayed concrete: a breakdown of the main issues is shown in Table 1. The different sources of shrinkage and mitigating these with different measures constituted a main part of the experimental work.

2.1 *Experimental program*

In order to address the performance shortcomings of the existing wet mix sprayed concrete, a sequence of main experimental work phases was established. These phases are summarized and are shown in Table 2.

Table 1. Breakdown of the cracking problem, focusing on shrinkage and crack widths and distribution.

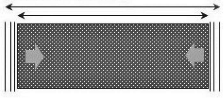
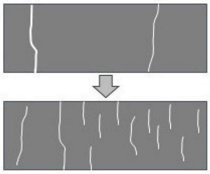
Main issue	Material property	Mitigating effort
SHRINKAGE 	Autogenous and plastic shrinkage measured 0.2 – 0.4 mm/m for standard sprayed concrete SUPERCON goal <0.2 mm/m DRYING SHRINKAGE measured up to 1 mm/m	Reduced binder content – replacement of cement with lime powder or fly ash. Shrinkage reducing agent Avoid drying of surface after spraying.
CRACKING 	SUPERCON goal <0.4 mm/m Crack widths 0.2-0.4 mm measured for rock support sprayed concrete. Crack widths <0.2 mm favourable SUPERCON goal <0.1 mm Rate of permeation through cracks reduced.	Fibre dose and type to achieve strain hardening. EVA polymer modification for low rate of permeation through cracks.

Table 2. Main experimental work phases.

Phase	Time	Main activity	Location	Main goal
1	2019/08-10	Mix design efforts tests	Laboratory*	Effect on performance of different constituent materials. Formulation of innovative mixes
2	2020/06	Sprayed concrete trial 1	Outdoor site, NTNU**	Detailed performance of existing standard sprayed concrete
3	2020/10	Sprayed concrete trial 2	Tunnel Svorkmo	Site preparation and full scale underground performance of standard existing sprayed concrete
4	2021/03	Sprayed concrete trial 3	Tunnel Svorkmo	First full-scale spraying of innovative mixes
5	2022/04	Sprayed concrete trial 4	Tunnel Drammen	Follow-up full-scale spraying tests of innovative mixes

* MasterBuilders Solutions laboratory, Germany. Bekaert laboratory, Belgium
** Outside SINTEF and NTNU concrete laboratories, Norway

2.2 *Developed mix designs, tested mixes*

The normal cement content for sprayed concrete is in the range of 480 – 505 kg/m^3, mostly using a CEM II fly ash cement. The reason for such high cement content has been to achieve the early strength requirements, including at relatively low temperatures. In view of this research there was an obvious potential to reduce the cement content considering a lower requirement on the early age strength.

Mix designs were formulated to verify the effect of the use of the innovative constituent materials and were formulated with a different functionality in mind compared to a rock support sprayed concrete. Contrary to a rock support sprayed concrete with severe requirements on early age strength development, in this case the need for early strength is pure related to the concrete not falling of the surface during overhead spray-application. The intention with the mixes 5 and 6 was to investigate the practical feasibility of significantly reducing the cementitious binder content. An overview of the innovative constituent materials with the intended effect on the concrete properties is shown in Table 3. The final mixes tested in the final phase 5 are shown in Table 4.

Table 3. Selected innovative constituent materials included in the development program based on the results of the initial laboratory test phase.

Constituent material	Dosage range	Intended effect
Limestone filler	100 – 150 kg/m^3	Partial pozzolanic replacement of cement, filler for achieving necessary matrix volume. Lower carbon footprint
Fly ash	80 – 120 kg/m^3	Pozzolanic replacement of cement. Lower carbon footprint
Hydration accelerator	1 – 2.5% *	Boost early strength at lower binder content
Shrinkage reduction agent	0.5 – 1% *	Significantly reduce shrinkage
EVA polymer	20 – 25 kg/m^3	Increased ductility as failure strain in tension
Steel fibres 3D, 80/30	25 – 40 kg/m^3	Significantly increased strain hardening

* dosage in percentage of cement weight

Table 4. Test mixes for the final phase of the experimental program.

Mix design number						
Constituent materials at batching plant	1	2	3	4	5	6
CEM II/B-M [kg/m^3]	471	470	450	467	372	320
Elkem microsilica fume [kg/m^3]	20	20	19	20	20	17
Matrix volume [l/m^3]	438	438	438	438	438	380
Water/binder ratio	0.42	0.42	0.42	0.42	0.42	0.42
Superplasticizer [% by cement mass]	0.9	0.9	0.9	0.9	1.1	1.1
Air entrainment [%]	0.1	0.1	0.1	0.1	0.2	0.2
Steel fibers 3D 80/30 [kg/m^3]	40	40	40	40	40	40
0-8 mm natural sand, [kg/m^3]	1403	1403	1403	1403	1403	1506
Limestone filler	123	122	117	122	122	105
Fly ash	-	-	-	-	98	84
Hydration accelerator [%]	-	2.6	2.6	2.6	3.2	3.3
Shrinkage reduction agent [%]	-	-	-	0.5	0.6	0.7
EVA polymer [kg/m^3]	-	-	20	-	-	-

3 RESULTS AND DISCUSSION

3.1 *Fresh concrete properties*

Well flowing concrete was achieved for all concretes, with slump retention values in the range of 240-260 mm measured at the spraying location in the tunnel 30-45 minutes after batching.

Fresh concrete temperatures were in the range of 21-25 °C at the spraying location. The air content in the fresh concretes was measured to approximately 4%.

3.2 *Shrinkage*

Shrinkage was measured directly on the surface of the sprayed concrete panels. Figure 5 shows the setup of shrinkage measuring points installed in a triangle. Figure 6 shows the effect on measured shrinkage of two different set accelerator dosages compared to the unaccelerated concrete. One set of panels was covered with plastic and the other set was left exposed to the ambient climate. The panels covered with plastic experience autogenous and plastic shrinkage, whereas the uncovered panels were also exposed to the drying shrinkage. Note that the heat generation caused by the accelerator contributed to quite high maximum initial temperature and thus subsequent temperature contraction during the first day. Hence, the measured length changes in Figure 6 also includes temperature contraction. Panel temperature was not measured here, but measurements from other parts of the project give reason to suggest that probably at least half of the measured length change is temperature contraction. The other measured effects on shrinkage of the different mix designs are summarised in Table 5.

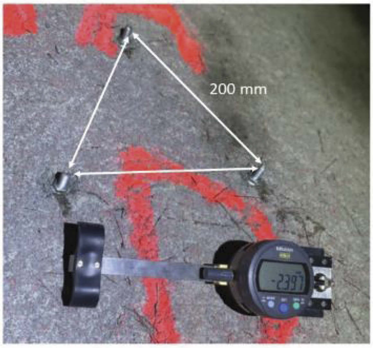


Figure 4. Procedure for direct measurements of shrinkage on the surface of sprayed concrete.

The measured effects of the set accelerator, suggest that a low accelerator dosage of 3% contribute to a higher shrinkage compared to the higher dosage of 7% in either cases with both covered and uncovered specimens. The higher dosage contributes to more rapid strength gain at early age, and hence, the concrete will very likely exhibit sufficient strength combined with sufficient ductility at early age. The lower dosage of accelerator will very likely initiate a quick enough setting to cause a temperature increase, but without a significant strength and deformation modulus gain. Hence, the measured tensile deformation is higher for the lower accelerator dosage.

The results of measurements in the tunnels show that the sum of thermal and autogenous shrinkage of the present sprayed concretes is rather low and considered to be too low to alone give cracking of the sprayed layer. But drying conditions corresponded to approximately 20 °C and 50-60 % relative humidity, giving higher total shrinkage. Avoiding drying out, the shrinkage results indicate that a completely covered specimen without any effect of set accelerator should remain uncracked.

3.3 *Water permeation through cracks*

Water permeation tests were done on cracked specimens with precisely controlled crack widths. The specimens were cracked with the crack width controlled to achieve target crack widths, which were measured by digital image correlation. Water pressure was applied on one side of the specimen and the permeating water was collected in a measuring cylinder. The mass of permeating water was measured and logged every second. The flow rate coefficient,

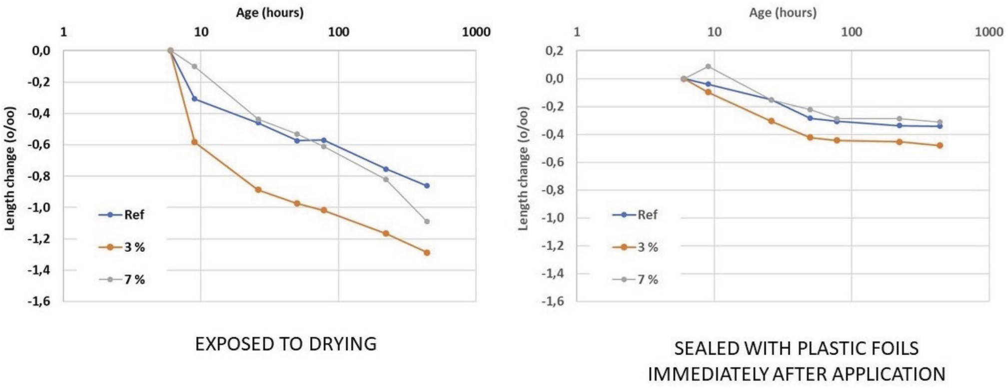


Figure 5. Results from shrinkage measurements from phase 2, showing the effect of two different set accelerator dosages and dry-out compared to completely sealed specimens.

Table 5. Measured effects on shrinkage of different innovative mix design effort.

Mix design effort	Measured effect on shrinkage
Reduced cementitious binder content	Not measurable
Limestone replacement of cementitious binder	Slightly favorable
Flyash replacement of cementitious binder	Slightly favorable
Shrinkage reducing agent	Significant reduction
Hydration accelerator	Not measurable
EVA polymer additive	Increased shrinkage

ζ is the measured permeation divided by the theoretical, through an ideal, straight, smooth and continuous crack (Ripphausen, 1989). A graph of the flow rate coefficient against the maximum crack width is shown in . The results show us that above crack widths of 0,15 mm the flow rate coefficient increases in an exponential manner with increasing crack width in standard sprayed concrete. Whereas with inclusion of the EVA based polymer admixture, the flow rate decreases much less and more linearly with increasing crack width.

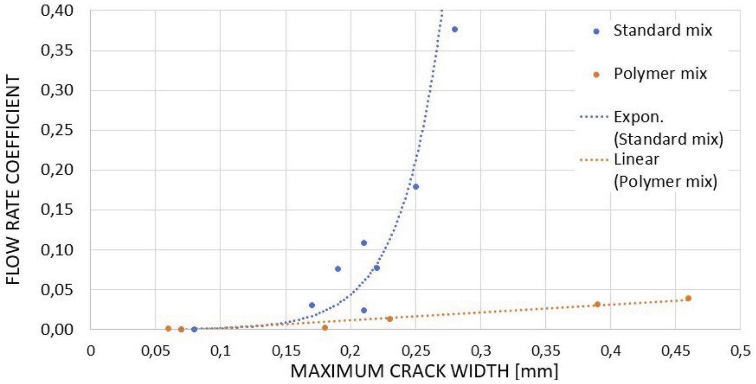


Figure 6. Graph of flow rate coefficient against maximum crack width for water permeation tests through cracked specimens.

3.4 *Strain hardening properties of steel fiber reinforced sprayed concrete*

Strain hardening properties were investigated by testing cut beams from spayed panels according to NS-EN 14651 (2005) and round panel energy absorption tests according to Norwegian Concrete Association (2011). The mean measured energy absorption for the two series were 1184 J and 1282J for 40 kg/m^3 of 4D 65/35 and 3D 80/30 respectively. This result compares to 1000J for the highest requirement for rock support sprayed concrete. The results from the beam tests are shown in.

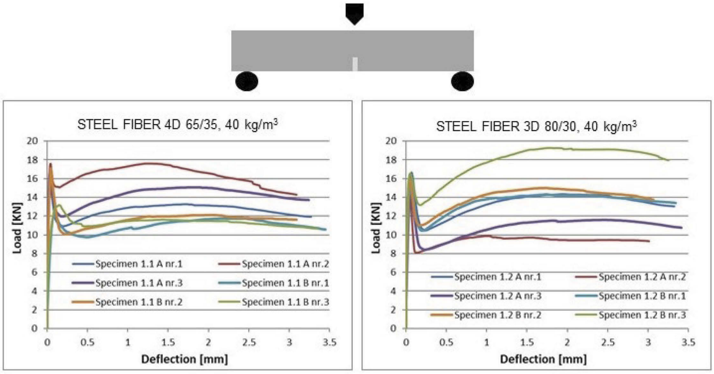


Figure 7. Results from two test series according to NS-EN 14651 on beams 150 mm by 150 mm by 600 mm sawn from sprayed specimens.

3.5 *Practical spray-application on overhead substrate and on wet spots*

Achieving successful spray application with high slump concrete combined with high fiber dosages was the main goal of the overhead spraying trial. Furthermore, the mixes with low cementitious content were tested for overhead spray feasibility considering the potentially insufficient early strength development. Early age compressive strengths were measured and found to be relatively low compared to typical requirements for sprayed concrete for ground support. Despite this result, none of the sprayed mixes showed any sign of slabbing off the substrate. Scan data indicated sprayed concrete thicknesses overhead of up to 250 mm.

4 CONCLUSIONS

The main findings can be summarized as follows:

- The technical functionality of a waterproof sprayed concrete, as well as functional sprayed concrete with much lower cement content was demonstrated.
- The design for which this technical solution has been developed, has been investigated for a drained tunnel concept in jointed hard rock with hydrostatic pressures of maximum 0,5 MPa.
- Significant shrinkage has been found to be driven by a combination of drying out and thermally induced expansion and contraction at early age.
- Mix design efforts to reduce the autogenous shrinkage have limited effect. An innovative shrinkage reducing agent did reduce the measured shrinkage.
- The use of EVA polymer in the concrete mix significantly reduced permeation through cracks in the concrete.
- Fresh concrete temperatures in the range of 20-23 °C seems to be optimal.

- Fresh concrete logistics and time of spray application after batching is more sensitive than for normal sprayed concrete. The tested mix design efforts imply start spraying after maximum 60 minutes after batching.

The executed test phases have increased the knowledge of the effect of different innovative mix design possibilities. The results provide a good basis for further optimizing the details in mix designs, the batching production process, fresh concrete logistics and spray application details.

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