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Permanent sprayed concrete as final lining – results from the Norwegian SUPERCON Research Project

Norway, where most tunnels are built in competent rock

Norway has a long tradition of building tunnels using a particular method. Since most excavated rock is very competent, only very light structural support is needed, primarily comprising a combination of rock bolting and fiber-reinforced sprayed concrete. This approach is often complemented by systematic pre-excavation grouting to significantly reduce water ingress from joints and act as a shear-blocking system. In essence, tunnel excavation meets competent material that needs very little support. Norway, however, experiences cold winters, and any ice accumulation behind sprayed concrete can affect its structural functionality. To alleviate the risk of ice and to improve aesthetics, most tunnels have a suspended "inner lining" of precast concrete elements for the side wall and a suspended insulated layer covered with sprayed concrete for the crown. This covered insulation layer is also often used for the side walls. A systematic steel rod pattern is used for the "inner lining" suspension.

The consequence is that any potential rock movement remains well hidden behind the "inner lining," making inspection and maintenance measures challenging to carry out properly.

Therefore, a new approach to support and waterproof tunnels involving less concrete and the related CO_2 emissions was needed.

During many deliberations, it was agreed that waterproof sprayed concrete with no suspended elements was the final lining and that no further waterproofing was the desired solution. The need for additional pre-excavation grouting was acknowledged. The challenge would be to spray-apply concrete that is crack-free and watertight.

The SUPERCON research project accepted the challenge, which we will outline below. Fig 1 shows the conceptual model for a final lining structure with the SUPERCON concept.

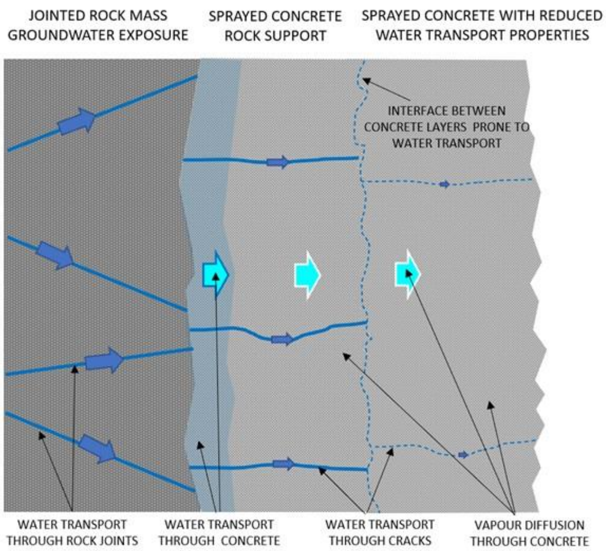

Fig. 1 Conceptual layout with a section of a complete lining structure from rock mass to lining surface. A two-layered system is envisioned with the layer in contact with the rock mass constituting the rock support and the inner layer having reduced water transport properties [2]

Testing program

Tunnels excavated in hard rock experience little to no deformation so that sprayed concrete linings do not undergo compression to the same extent that soft ground tunnels do. Sprayed concrete is, therefore, expected to demonstrate significant shrinkage behavior, most likely caused by drying and thermal contraction after placing with some strength and stiffness gain, which had to be proven. The test program, therefore, focused on minimizing the formation of cracks in the fresh-applied layers to maintain the watertightness properties of the high-quality materials used.

Global warming was the second driver in the choice of materials. All concrete is manufactured with related high CO_2 emissions, creating the need for thinner, high-quality sprayed concrete layers.

At best, all the proposed mix designs can be sprayed with additional “CO_2-reduced” features by reducing the clinker content in the mix.

The testing and research program was set up as follows:

- Initial mortar testing in the laboratory to improve our understanding of the shrinkage behavior of unloaded sprayed concrete samples and to understand the impact of added chemical admixtures better
- Laboratory spraying and testing of concrete mixes to confirm the essential findings from the extensive mortar tests
- Full-scale site testing to further confirm the findings and review the practicability of the proposed mixes
- Parallel Master and PhD papers that focus on particular issues, such as water transport in cracked samples
- A complete feedback loop in parallel based on the environmental suitability of the proposed solutions
- And a final recommendation

This paper will focus only on the technical aspects of the sprayed concrete.

Laboratory mortar tests

The mortar tests aimed to test the influence of multiple binder mixes with added construction chemicals on water loss and shrinkage.

Two series were tested. Series one focused on observing the binder combinations and the impact of adding each chemical to the standard plasticizer. Series two researched the specific aspects of series one, but only for a single binder combination.

All binder materials, the cement, the pulverized fly ash (PFA), and the limestone powders were from Norway. The reference mix comprised 450 kg of cement (CEM II/A) equivalent. In other mixes, the cement was lowered to 350 kg and 300 kg equivalent, respectively, and the missing binder was substituted by PFA or limestone powder.

The chemicals added in addition to the standard superplasticizer were a standard shrinkage-reducing agent (SRA) and an optimized SRA, a C-S-H (Calcium Silicate Hydrate) boosting admixture for the improved strength gain, a powder polymer, and finally, an 18 mm polypropylene microfiber. Structural fibers were not added to the laboratory mortar tests.

The water/cement ratio chosen was 0.45, and the targeted spread of 210 mm on the Hägermann table was achieved by adding a superplasticizer. All samples were accelerated with 5 % alkali-free accelerator (AFA), where the AFA dosage and the mixing regime were pre-tested to enable accurate reproduction.

The samples were immediately stored in climate chambers (Fig 2). The climate was set to 10 °C for one set of samples and 20 °C for the others, but always 65 % RH (relative humidity). Shrinkage readings began after unmolding and were taken regularly, starting as early as possible. In all cases, after four and the latest 8 hours (mixes without C-S-H booster). The water loss before the reading was recorded on a scale and added to the total. Cube strength was measured after 1, 2, 3, 7, 14, and 28 days. Shrinkage was recorded over 2 months. In total, 39 series were tested.

Fig. 2 Mortar samples in the climate chamber

Series One – water loss

Series one looked into water loss and shrinkage of mixes with only a single admixture added.

The measured water loss was assumed to be higher than in most publications since these laboratory tests were executed on accelerated samples, providing higher porosity and allowing earlier length change measurements. The water loss was recorded immediately, and the initial weight was set as the basis for the percentage considerations. Until demolding, only the top surface was uncovered, but after demolding, all 6 sample surfaces were exposed to the environment to provoke differences (Fig 2). The water loss was set to the total water added (water in the mix, water in the C-S-H boosting admixture but excluded water from other chemicals). The samples were stored in the climate chamber at the set conditions.

Within the first week, most tests demonstrated a total water loss of 40-45 % (of the total added water to its original weight at test start), with the most loss occurring on day one (about 2/3), see Fig 3. Two-month water loss was equivalent to the one-week readings. The exception was the 300 kg cement with 150 kg limestone mixes, where the one-week readings were lower at 35-40 % loss, but after two months, they were also at 45 %. The chemicals added did not cause significant differences but confirmed that the “plain cement” always displayed the highest water loss and that the optimized shrinkage-reducing agent (450_SRA R&D in Fig. 3) always performed better to significantly better than the standard SRA and the addition of fiber was of little influence. It should also be pointed out that up to about 10 % of water loss has already happened in mold within 4 to maximum 8 hours.

The key learning was that the water loss that potentially causes shrinkage happens quicker than previously assumed and that any countermeasures at job sites must be applied “immediately.”

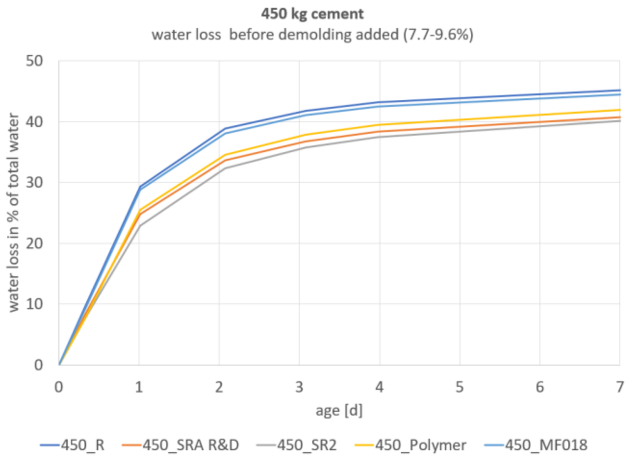

Fig. 3 Water loss of the mix with plain cement

Series One – shrinkage

Below is a selection of shrinkage measurements (Graf-Kaufmann); see Fig. 4. It must be noted that the addition of the C-S-H boosting admixture was extreme and much higher than would ever be used on site. This was to enable early demolding and provoke/accelerate shrinkage.

Fig. 4 shows the optimized SRA's positive impact on shrinkage reduction. Mixes with 450 kg cement, 350 cement + 100 kg fly ash, or limestone powder were tested with and without the optimized SRA's addition. The addition of SRA yields significantly lower values, which is highly beneficial for fresh concrete with the associated low tensile strength.

The key learning of series one was again that shrinkage happens fast and countermeasures must be employed immediately.

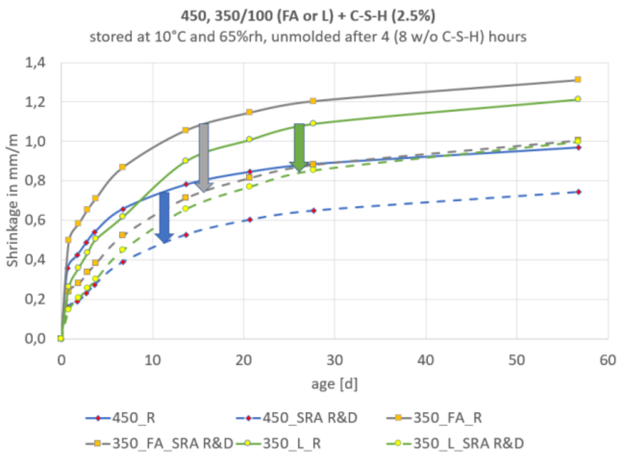

Fig. 4 Shrinkage of 3 different mixes (450/0; 350/100 fly ash; 350/100 limestone powder) positive effect of optimized SRA. High shrinkage provoked by overdosed C-S-H

Series Two

Series two examined aspects such as temperature influence, 10 °C storage vs. 20 °C, and the influence of an admixture combination, but for a single binder combination only (300 kg cement, 150 kg limestone powder, C-S-H admixture for strength gain added).

Fig. 5 shows the influence of the storage temperature (in both cases at 65 % RH), where the 10°C storage always yielded higher shrinkage. It is assumed to be influenced by the lower strength at test age.

The lowest shrinkage at 10 °C storage was recorded for the following combination: Binder (300/150 limestone powder), C-S-H boosting admixture, optimized SRA, and polymer. The results were over 3 times lower than the reference.

Spray application tests

The spraying testing program aimed first to establish the shrinkage data from a reference base of standard rock support sprayed concrete. Subsequently, a series of sprayed concrete mixes were tested to measure the effect of each mix design item included in the formulated new mixes. The formulation of the mixes for spray application testing was derived from the results of laboratory tests.

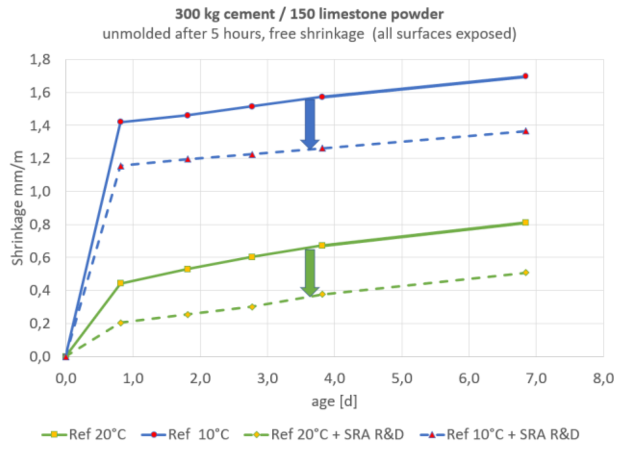

Fig. 5 Temperature and optimized SRA influence on shrinkage

The testing program aimed at a progressive development of mixes through the practical application in full scale on tunnel surfaces underground in several stages. In this way, laboratory specimens were prepared early from sprayed test fields. The mixes' following development and optimization process could then be based on reliable results obtained from realistic sprayed concrete in an underground setting.

The main test program consisted of the following full-scale site spraying campaigns:

- Reference base: Spraying of standard sprayed concrete for rock support
- Spraying of the first array of 8 innovative sprayed concrete mixes, preparation of laboratory specimens according to an established laboratory test matrix
- Spraying of the second array of 6 innovative sprayed concrete mixes, narrowing the number of mixes, emphasizing the overhead sprayability and resistance to wet spots
- Spraying of a third array of 4 innovative sprayed concrete mixes, testing one central concept and the effects of reduced cementitious binder content

The results from one test campaign formed the basis for the layout and details of the following campaign. In this way, mix design details and the number of mixes could be narrowed down to the mix type which proved to perform. Hence, the required time frame for this progressive testing program was approximately three years.

The key performance issue was shrinkage resulting in cracking, the main adverse effect of shrinkage. Hence, the technical target of the testing was to measure the impact of the different mix design efforts on shrinkage and cracking. In parallel to the attention to shrinkage and cracking, the spray-application performance was emphasized. The details in the spray application related to functional early strength to facilitate the adhesion of the freshly sprayed concrete on the existing substrate of rock support sprayed concrete and achieving an even spray performance to ensure as much homogenous compaction as possible with a minimum pulsation in the spray.

Tab. 1 shows the main test mix array. The main issue is reducing the cementitious binder content and replacing it with non-cementitious substituents, fly ash, and limestone powder. A C-S-H boosting admixture added to the base mix at the batching plant compensates for the reduced cementitious binder content's negative effect on the early strength performance.

Tab. 1 Overview of sprayed concrete mixes tested in the second full-scale trial in Drammen

	Mix design number					
Constituent materials (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	-	-	-

Test specimens were consistently prepared from sprayed panels, with monitored age and physical curing history. The spray performance was monitored to verify the progressively developed mixes' practical constructability.

Results

The effects of several of the innovative mix design efforts could be established. Shrinkage and water transport properties on cracks were considered the most important and are discussed here. Shrinkage was measured directly on a triangle of three studs, drilled into the concrete slabs of 600 mm by 600 mm and 150 mm thickness at approximately one hour's age. A set of panels was left exposed to the ambient air humidity, hence simulating total shrinkage, including drying-out shrinkage. The other set of panels was immediately sealed in plastic. The setup for direct shrinkage measurements on sprayed specimens is shown in Fig. 6.

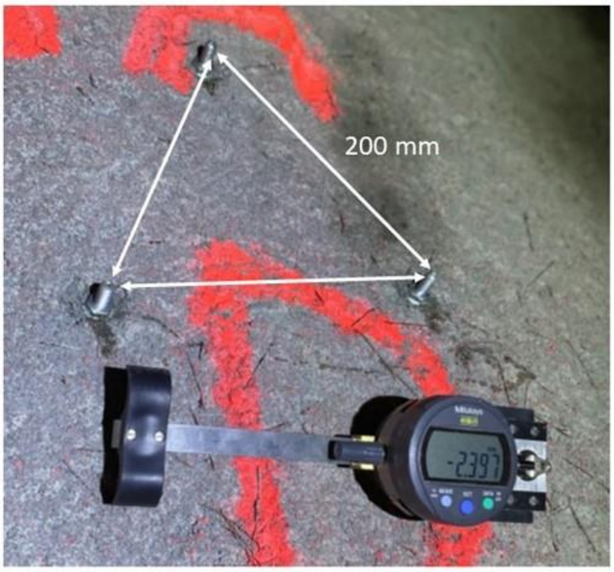

Fig. 6 A triangular setup of studs was used to directly measure unrestrained shrinkage on sprayed concrete panels and restrained shrinkage on the rock wall.

The findings relating to shrinkage can be summarized as follows:

- Limestone and fly ash substituents give lower long-term total shrinkage. The measured effects on short-term shrinkage of lower cementitious content and fly ash and limestone substituents were inconclusive
- SRA addition yields lower total shrinkage
- Polymer powder addition gives higher drying-out shrinkage
- The measured restrained shrinkage on the rock wall is significantly lower than the unrestrained autogenous shrinkage measured on panels

Fig. 7 shows a set of measurements comparing total unrestrained shrinkage, including the effects of drying out and autogenous unrestrained shrinkage measured on panels.

The drying-out shrinkage exposure occurred in an access tunnel for an underground hydropower plant in operation. The panels were exposed to low airflow ventilation (<0.1 m/s) and relative humidities in the tunnel air ranging from 80-90 %. The measured values for drying-out shrinkage are notably high, considering the favorable exposure conditions in the tunnel air. Construction ventilation during drill-and-blast tunnel excavation will pose a significantly more severe drying-out exposure than the testing conditions in this trial. The comparison shown in Fig. 7, where covered samples simulate ideal curing compared to samples exposed to ambient humidity and ventilation, already highlights the need for proper curing measures immediately after the concrete spraying.

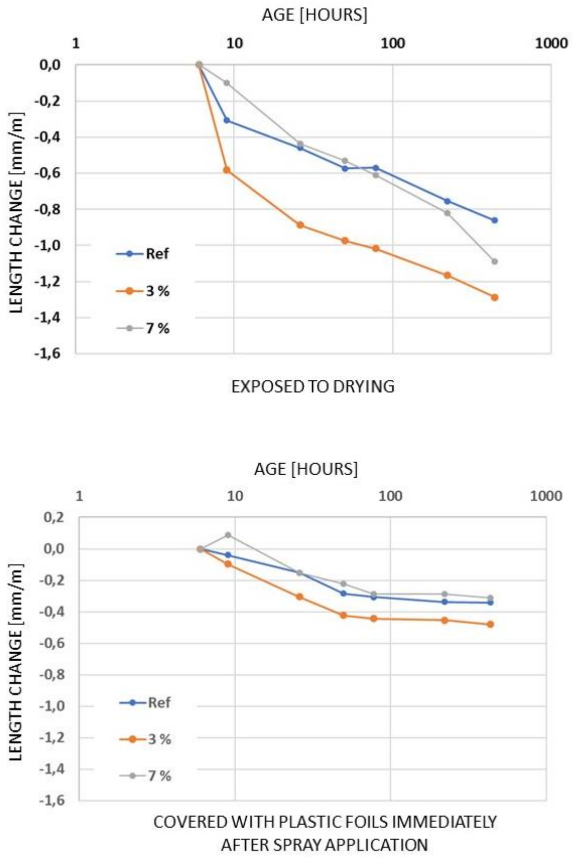

Fig. 7 Measured unrestrained shrinkage for a reference mix sprayed on panels 150 mm thick panels. Upper diagram: panel exposed to drying (total shrinkage). Lower diagram: panel sealed with plastic foil immediately after spry application (autogenous shrinkage)

Effects of polymer additive on water transport in cracks

The measured effect of polymer additives on ductility in the form of increased failure strain in uniaxial tension was minor. However, the polymer additive had a significant measured impact on the water transport in cracks. A controlled cracking of disc-shaped specimens was carried out, followed by a controlled water penetration test in the crack. Concrete with polymer additive showed significantly lower water transport through the same crack width than concrete without polymer. The test setup is shown in Fig. 8, and the measured water transport comparing a reference concrete with a polymer powder-modified concrete is shown in Fig. 9. The measurements show that water transport for the reference concrete increases significantly with increasing crack widths above 0.15-0.2 mm. In contrast, the concrete with polymer powder additive indicates only a slight increase in water transport at increasing crack widths.

Water transport in cracks is considered the main degrading element, so any reduction is beneficial. Hence, adding polymers to the base mix design is worth considering.

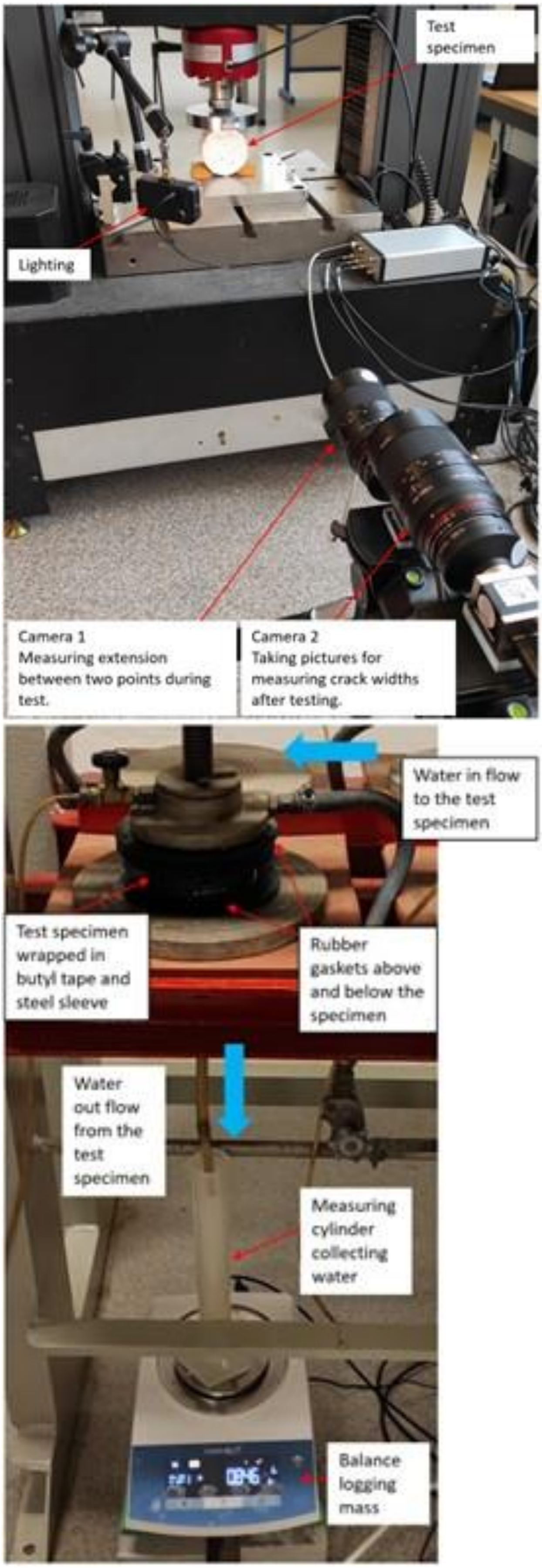

Fig. 8 Left, the experimental setup for controlled tensile splitting for precise crack widths. Right: experimental setup for measuring water permeation through cracked discs [3]

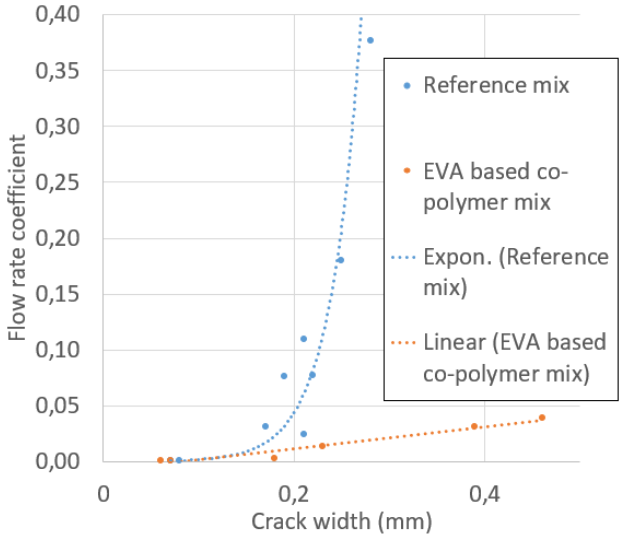

Fig. 9 Controlled water transport through cracks. Measured flow rate coefficient against maximum crack width for permeation through cracks in specimens from a reference mix and a polymer mix [3]

Observed effects on fresh concrete properties and overhead spray adhesion performance

The measured early age strength development was low, about J1, for the mixes with significant binder substituents. An important point was, therefore, to investigate the overhead adhesion performance. The binder composition, exhibiting a low cement content, favored using a hydration accelerator (C-S-H booster). A high slump fresh concrete property was essential to provide sufficient logistics buffer timewise when the effect of the hydration accelerator initiates. Slump retention values were targeted at 240-260 mm, with a fresh concrete temperature target of 20-22 °C at the beginning of spraying. The achieved overhead spray performance was remarkably good, exhibiting low pulsation, sound, and “wet” compaction on the wall and an impressive overhead sprayed thickness of more than 200 mm without adhesion failure. Photos in Fig. 10 illustrate the fresh concrete and overhead spraying performance.

Fig. 10 Spraying of high-slump concrete, achieving exceptional immediate adhesion

Effects on shrinkage and cracking of climatic conditions during the spray application

During advancing excavation, the latest field trial in the Hestnes railroad tunnel was executed on the rock wall approximately 300 m behind the tunnel face. This meant exposing the sprayed concrete surface to airflow speeds of 0.3 – 0.6 m/s. For 30-45 minutes after each excavation blasting, air flow speeds were 1 – 1.5 m/s. Despite watering the sprayed concrete surface at intervals for the first 48 hours, the drying effect of the construction ventilation during the advancing drill-and-blast excavation caused significant shrinkage-induced cracking. We could not measure this precisely, but cracking and reoccurring leaks through the sprayed concrete were visible.

At a later stage, after the breakthrough and completion of the excavation, the forced ventilation was terminated. Natural ventilation through the 3 km long tunnel resulted in prevailing airflow speeds lower than 0.1 m/s. Several sections of the tunnel with minor water seepage points in the form of damp spots and minor drips were covered with reference sprayed concrete, resulting in a dry final sprayed concrete surface. The relative humidity was in the range of 90-100%, frequently with periods of several days with RH 100%, which could be observed as extensive condensation on the tunnel surface. This is a normal phenomenon observed in tunnels during warm summer weather in July to September in Scandinavia, during which the rock mass temperature is lower than the outer air temperatures.

The observed effects demonstrate the need to create and maintain high humidity exposure and reduced ventilation speed to avoid excessive shrinkage and cracking.

Further work will include detailed measurements of climatic conditions in the tunnel during and after the spray application and studying the effects of watering the freshly sprayed concrete surface on shrinkage.

Summarizing comments

The SUPERCON research project [1,4] demonstrated two technical targets: shrinkage reduction and reduced water flow in cracks. Fly ash and limestone as cement substituents increase resistance to long-term shrinkage-induced deformations during cyclic drying out and wetting.

The project could not identify an effort in the form of chemical additives or binder substituents that could significantly reduce the drying-out shrinkage without additional curing measures. The latest field trials showed that maintaining high air humidity for several weeks significantly reduces concrete shrinkage.

Further work will emphasize increased performance to resist water ingress points of a certain magnitude, maintaining a concrete layer with minimum water permeation.

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