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

Waterproof sprayed concrete with improved sustainability performance

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ABSTRACT: Sprayed concrete in combination with rock bolts has successfully been used for permanent rock support in tunnels for decades. The main shortcoming is that sprayed concrete alone is unable to function as permanent waterproofing in tunnels that requires a dry interior tunnel surface. Therefore, the trend is final inner linings of cast-in-place concrete or waterproof pre-cast segmental lining. In hard rock conditions such concrete linings often represent an excessive structural design, resulting in unnecessary costs, excavated volume, construction time and CO_2 emissions. The research project SUPERCON, aims to develop a waterproof sprayed concrete, as an alternative to the currently used linings. The research results indicate the feasibility of a waterproof sprayed concrete. The concept is presented and discussed. To emphasize the effect of the concept, a comparison is made on CO_2 emissions from cement and excavated volume of rock for four different lining types used in road and railroad tunnels.

1 INTRODUCTION

Sprayed concrete has been successfully used for permanent rock support for several decades. The final inner lining for waterproofing and esthetic purposes has been realized by using cast-in-place concrete in many cases, or different types of drainage and thermal insulation shield structures for drip protection of the carriageways and railroad tracks.

The water management in the Scandinavian hard rock philosophy is based on drained tunnels, in which the water seepage is controlled through probe drilling and pre-excavation grouting (PEG) when required.

The hard rock ground support philosophy, which has been implemented in the Scandinavian countries, considers the rock mass as the main mechanically load bearing part of the tunnel structure. The rock support, consisting of a combination of rock bolts and sprayed concrete, has a function of maintaining an intact tunnel contour and a rock mass with as little as possible deformations to act as a self-standing structure. The main shortcoming is that sprayed concrete alone is unable to function as a permanent waterproofing in tunnels with strict requirements to no drips or wet surfaces on the interior tunnel surface. Therefore, the trend today is final inner linings of cast-in-place concrete with sheet membrane waterproofing or waterproof pre-cast segmental lining. Thus, in hard rock ground conditions the traditional use of concrete linings in many cases represent an excessive structural design, as it is not needed for rock support purposes, but to function as a permanent waterproofing.

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The excessive structural design using cast-in-place concrete or other lining structures used in the current practice, have a significant impact on cost, excavated volume of rock mass, construction time and CO_2 emissions. Several projects have been successfully completed with a lining system based on a combination of sprayed concrete and spray applied waterproofing membrane in a continuously bonded structure (Holter 2016). 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 research project SUPERCON (Sprayed sUstainable PErmanent Robotized CONcrete) aims to innovate a drained waterproof sprayed concrete, as an alternative to the currently used linings in road and railroad tunnels, to reduce excessive use of concrete and reduce the excavated volume of rock mass. This would further lower costs and reduce the construction time. The research project is currently being carried out at SINTEF, NTNU and NGI in collaboration with the tunnelling industry, as well as public owners.

2 TECHNICAL BACKGROUND

2.1 *Sprayed concrete, function as support and lining*

The rock support, consisting of a combination of rock bolts and sprayed concrete, has a function of maintaining an intact tunnel contour and a rock mass with as little as possible deformations to act as a self-standing structure. Under such conditions, the rock support will only be exposed to local loads and mostly receive very low loads when exposed to the weight of loose or deforming blocks of rock. A significant part of the lining will under such conditions be a mechanically passive structure.

The addition of fiber reinforcement or the use of mesh for sprayed concrete increases its post-cracking performance, also referred to as the sprayed concrete's toughness (Bernard & Thomas, 2020). The use of mesh is uncommon in Scandinavian countries with regards to hard rock tunnelling.

As of today (2020) the minimum required thickness for sprayed concrete in Norwegian traffic tunnels (rail, road and metro) is 80 mm. This thickness requirement is based on durability consideration in order to assure a service lifetime of 100 years under normal exposure conditions.

The continuous development of the sprayed concrete technology has led to improvements in several areas. These comprise improved constitutive materials and application process, improved technical performance of the in-situ sprayed concrete, increased predictability of the function of sprayed concrete linings, as well as more detailed and consistent technical specifications of material requirements.

The main function of a sprayed concrete lining in today's practice is to provide permanent ground support. This means the following:

– Material properties, in-situ applied, to suit the need for effective ground support in hard rock and weakness zones
– Long term durability under the given exposure to geomechanical, hydrogeological and geochemical conditions with respect to 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 hydraulic conductivity and is literally impermeable from a practical perspective in a tunnel. Furthermore, the sprayed concrete material exhibits a significant water vapor permeability. Subject to the gradient in relative air humidity, in reality the gradient in the partial pressure of water vapor, from the tunnel air to the concrete pores near the rock-concrete interface, a moisture transport through a sprayed concrete lining in the form of vapor transport from the rock mass to the tunnel air will take place.

2.2 *Layout of lining*

Traffic tunnels in hard rock have traditionally in Scandinavian practice 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). In order 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 tunnel design method. The tunnel structure will be permanently drained, as illustrated in Figure 1. Recent technical developments have led to improvements of the drip protection lining system in the form of concrete segments for highway tunnels with high traffic density. For railway tunnels, the trend has been to implement the central European cast-in-place concrete lining methodology (Holter et al. 2013). The two lining systems are shown in Figure 2.

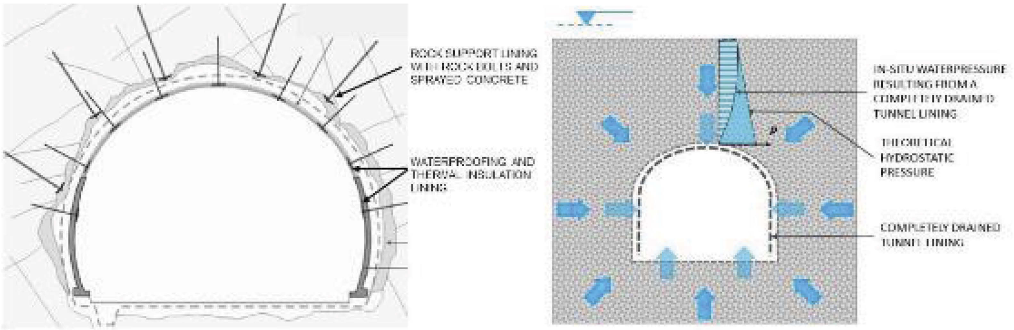

Figure 1. Principal sketches of drained tunnel lining system in a rock tunnel in Scandinavian practice. Left: The layout of the lining system (after Broch et al. 2002) Right: The in-situ groundwater pressure situation around a completely drained tunnel.

Figure 2. Photos of two completely drained lining systems from modern traffic tunnels. Left: The Nordic drip and freeze insultation lining system based on concrete segment structure. Courtesy Å. Homleid. Right: the conventional cast-in-place concrete lining system, Ulvin railroad tunnel, Norway.

3 LAYOUT OF TECHNICAL SOLUTION WITH WATERPROOF SPRAYED CONCRETE

The functional perspective for the SUPERCON lining concept originates from the documented properties of undrained and partly drained concrete lining with waterproofing membrane (Holter 2016). In a hard rock tunnel this lining concept utilizes the effect of the increased hydraulic conductivity in the excavation damage zone (EDZ). The water that seeps through fissures and fractures in the rock mass outside the EDZ, is drained through the EDZ towards the invert of the tunnel, reducing the groundwater pressure close to the lining, as illustrated in Figure 3. The water in the invert is collected in the tunnel drainage system. The drainage effect of the EDZ has been investigated in four different research works (Holter 2014, Holter 2015, Nilsen 2019 and Aas 2020). The draining effect of the EDZ has been investigated for maximum 5 bar of hydrostatic water pressure.

The proposed SUPERCON lining, with a waterproof sprayed concrete, will consist of a regular sprayed concrete layer for rock support purposes covered by a waterproof sprayed concrete as the inner and final layer. Figure 3 shows an illustration of the layout for a lining concept with waterproof sprayed concrete. The proposed lining system has many similarities to the system which uses sprayed concrete and a waterproofing membrane (Holter 2016).

The SUPERCON project has investigated the main sources of seepage through the concrete, to fully understand the challenges a watertight sprayed concrete need to overcome. Further, innovative mix designs with significantly reduced cement content have been tested in laboratory scale and full-scale tests in tunnels. Some of the sprayed concrete mixes have shown very good performance regarding reduced shrinkage induced cracking and reduced water seepage though artificially made cracks. Some of this work has been published in Holter et al. (2023).

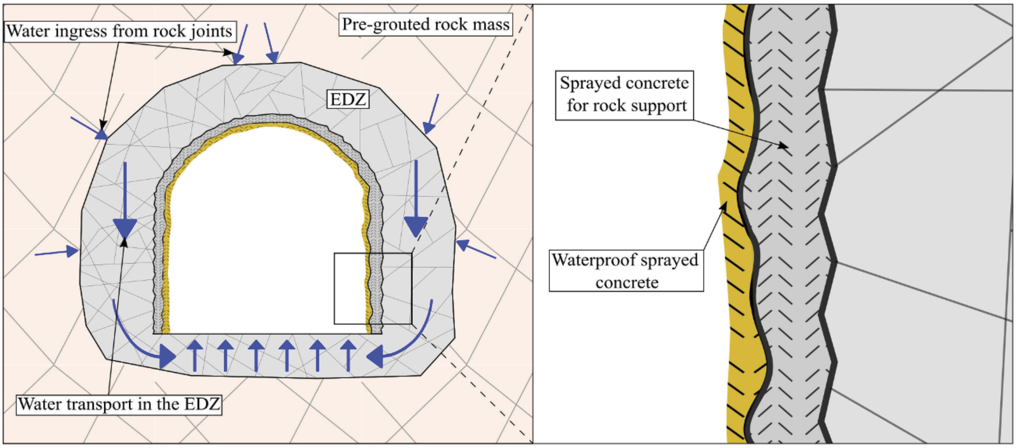

Figure 3. Illustration of the concept with waterproof sprayed concrete with a partly drained tunnel. Left: shows the effect of the EDZ. Right: shows the rock support of sprayed concrete in grey, and the waterproof sprayed concrete in yellow.

4 ENVIRONMENTAL FOOTPRINT ASSESSMENTS

For the assessment of environmental footprint from different lining types, three types of recently used linings in Norwegian tunnels are represented, in addition to the lining with the most promising sprayed concrete mix from SUPERCON. The lining types are briefly described as follows:

Lining type 1 (Cast-in-place) is common during excavation with drilling and blasting; the first stage of the lining is the initial rock support which includes a layer of sprayed concrete and rock bolts, followed by a levelling layer of sprayed concrete. The final layer of the lining is concrete casted by the use of formwork. This type is commonly used in railroad tunnels where the load from the air surge caused by passing trains is heavy.

Lining type 2 (pre-cast segmental lining) is an example from the recently built Follo Line project in Norway, a twin tube railway tunnel connection between Oslo and Ski, excavated by using

TBM's. The segmental lining was installed shortly behind the TBM. The annular space between the pre-cast lining and the rock mass was backfilled with a cementitious grout (Kalager & Gammelsæter, 2019).

Lining type 3 (Pre-cast concrete elements), is the Norwegian traditional system, typically used in road tunnels. The first stage of the lining includes a layer of sprayed concrete and rock bolts, to establish an initial and permanent rock support. Further an inner shield is constructed with pre-cast elements in the walls, and water and frost protection in the arch consisting of PE-foam mats, covered with sprayed concrete as fire protection. An annular space of approximately 50 cm between the sprayed concrete and the inner shield remains open.

Lining type 4 (waterproof sprayed concrete lining) is the proposed innovative lining presented above. It consists of a layer of sprayed concrete and rock bolts for the permanent rock support, and then a layer of the waterproof sprayed concrete (SUPERCON concrete).

According to Ecoinvent 3, based on Wernet et al. (1989) plain concrete with cement with 200 kg/m^3 CEM II/B approximately 88% of the CO2-equivalents are from cement. To emphasise the environmental effect regarding the carbon footprint, it is chosen to present basic examples by mainly using the cement in the concrete. The calculations consider A1-A3, which is the acquiring of raw materials, transport to manufacturing facility, and the manufacturing process (NS-EN 15804, 2013). Hence, this perspective of this comparison of the environmental impact of the different types of tunnel linings is conservative.

Table 1 shows the cement content of concrete and thickness of the different elements in each type of lining for a tunnel with an inner diameter (diameter of the theoretical profile) of 10.5 metres. For lining type 3 the PE-foam sheets are included in the CO_2 accounting, as this type of water and frost protection is not required in the other types of tunnel lining.

Table 1. Overview of composition and thickness of four different types of tunnel lining.

Lining type	Description	CEM II/B [kg/m3]	Thickness [m]
1	SC ground support	470	0.1
	SC levelling layer	470	0.1
	Cast-in-place concrete lining	400	0.3
2	Pre-cast segmental lining	400	0.4
	Cement grout-based backfill	350	0.2
3	SC ground support	470	0.1
	Open space	0	0.5
	PE foam mat	0	0.04
	SC Fire protection	470	0.085
	Pre-cast elements	400	0.2
4	SC ground support	470	0.1
	SC Supercon	450	0.08

According to the EPD for Norcem Brevik FA CEM II/B-M (NEPD-227-1028-NO, 2020) the production process (A1-A3) gives approximately 582 kg CO_2-eq. per tonnes cement. According to the EPD for ISOLON TX Cross-linked PE foam the production (A1-A3) of PE foam mats gives approximately 14.6 kg CO_2 equivalents per m^2.

The bar plot in Figure 4 left, presents the calculated consumption of CO_2-eq. for the four different types of lining. Lining type 1 (cast-in-place concrete) is an approach that requires 4.5 tonnes cement per metre tunnel, which results in 2.6 tonnes CO_2-eq. per metre tunnel lining. Lining type 2 (Pre-cast segmental lining) requires 8.8 tonnes cement per metre tunnel, which results in 5.1 tonnes CO_2-eq. per metre tunnel. Lining type 3 (Pre-cast elements) requires 2.1 tonnes cement and 13 m^3 PE foam mat per metres tunnel, which results in a total of 1.4 tonnes CO_2-eq. per metre tunnel. Lining type 4 (multi-functional layer of sprayed concrete) requires 2.0 tonnes cement per metres tunnel which results in 1.0 CO_2-eq. per metre tunnel. Both the lining types 1 and 2 are extreme cases regarding cement consumption. For Lining

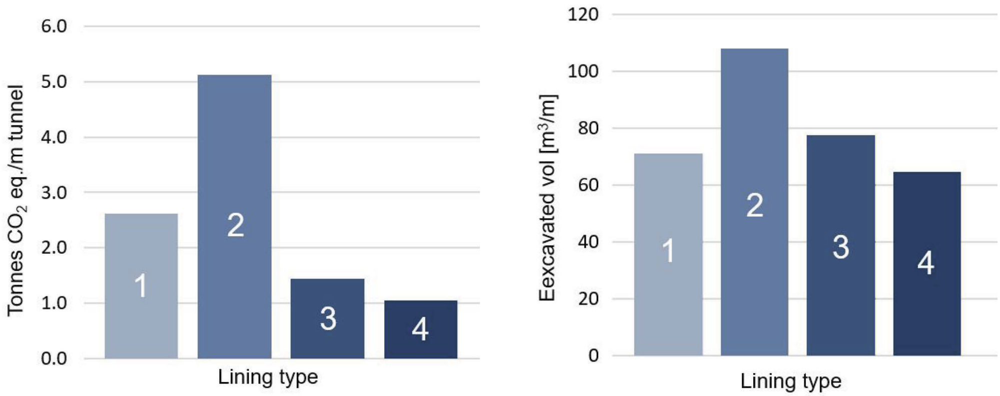

Figure 4. Left: CO_2 eq. per linear meter tunnel for cement used in the lining. For lining type 3, CO_2 eq. per production process of PE-foam mats are included. Right: Required excavated volumes needed to obtain a diameter of 10.5 meters theoretic profile for the four different types of tunnel lining.

type 2, pea gravel could be used instead of cement-based backfill, but the CO2 eq. from the concrete lining alone results in 3.5 tonnes CO_2-eq. per metre tunnel lining.

These types of heavy structures are mostly unnecessary in tunnels excavated in good quality rock masses with self-supporting properties, as frequently encountered in most Scandinavian tunnelling projects. Lining types 3 and 4 are quite similar compared to the other two lining types, but a reduction of approximately 300 kg CO_2-equivalents per linear metre tunnel is quite significant considering a large tunnelling project.

Furthermore, the lining types require different amount of space, which means different excavation volumes, to obtain the same theoretic profile of the tunnel, as shown in Table 1 and Figure 4. For a TBM-excavated tunnel (lining type 2), the excavated volume is significantly larger due to the circular shape, for tunnels excavated with drilling and blasting (lining type 1, 3 and 4) the space is horseshoe shaped, reducing the excavated volume. When comparing the lining types with similar excavation profile shape, the estimation shows that the traditional lining types 1 and 3 need respectively 10 % and 20 % more excavated rock mass than for the SUPERCON lining (lining type 4). This gives a significant environmental impact as it increases use of explosives, mass transportation and volume of blasted rock that need to be disposed.

Due to the relatively high cementitious binder content, sprayed concrete itself carries a high carbon footprint. The benefit in this context relates to the total required concrete layer thickness which can be significantly reduced and the reduction in excavated volume.

The preliminary SUPERCON mix has a slightly different composition than an ordinary sprayed concrete mix. A comparison of the CO_2 emissions for ordinary sprayed concrete and the SUPERCON sprayed concrete has been conducted, to demonstrate that the CO_2 emissions from waterproof spayed concrete does bring a significant change in the comparison between the lining types.

The reference mix, shown in Table 2, sprayed in the SUPERCON field trials at Drammen is used as a reference for ordinary sprayed concrete in this comparison. This mix design can be considered representative for rock support in Norwegian tunnelling. The calculation for the following considers A1-A3. Figure 5 shows that the total CO^2 eq./m^3 of the SUPERCON concrete is slightly higher than for the reference mix. CO^2 eq./m^3 is 316,4 for the reference mix and 355,7 for the SUPERCON mix. The major contributors to CO^2 emissions in both mixes are mainly cement and steel fibers, however the EVA polymer adds a sizeable CO^2 contribution in the SUPERCON mix. The addition of microsilica is not included in these calculations because it is considered a by-product of the industrial silicon and ferroalloy production. Several of the other SUPERCON sprayed concrete mix designs have the potential for even better performance compared to ordinary sprayed concrete regarding environmental impact.

Table 2. Constituents of reference mix and SUPERCON mix.

	Reference mix	SUPERCON mix
CEM II/B-M [kg/m^3]	471	449.7
Microsilica fume [kg/m^3]	19.6	18.7
Matrix volume [l/m^3]	438	438
Water/binder ratio	0.42	0.42
Superplasticizer [%]	0.9	0.9
Air entrainment [%]	0.1	0.1
Steel fibers 3D 80/30 [kg/m^3]	40	40
Aggregate, 0-8mm [kg/m^3]	1402.6	1402.6
Limestone filler [kg/m^3]	122.7	117.1
Hydration accelerator [%]	0	2.6
EVA Polymer [kg/m^3]	0	20.02

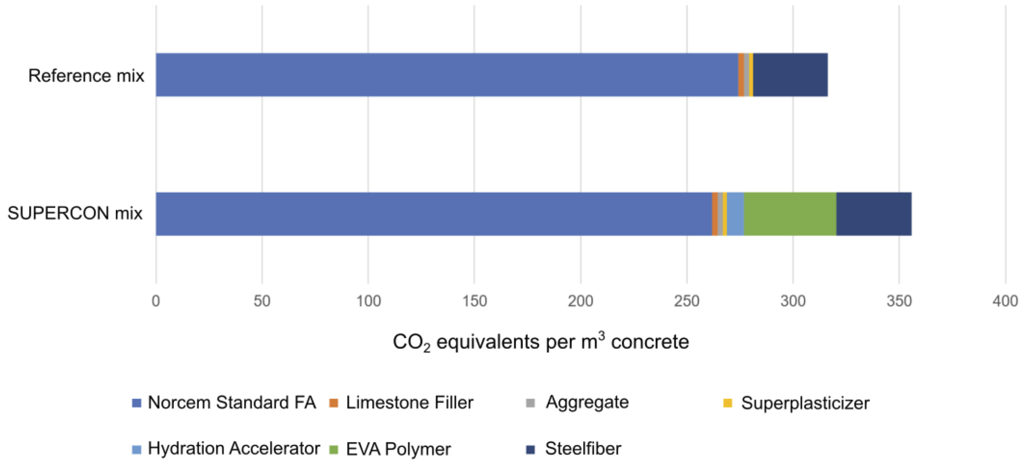

Figure 5. Comparison of CO_2 equivalents per cubic meter concrete for reference mix and SUPERCON mix for sprayed concrete.

These examples indicate that by optimizing the functionality of sprayed concrete to become a final inner lining, the carbon footprint from tunnel construction can be reduced to a large extent. Construction time and costs can also be significantly reduced.

5 DISCUSSION

With today's knowledge, the presented concept has the following areas of use:

- Applicable in hard rock with a self-bearing capacity
- Applicable in tunnels and caverns excavated by drilling and blasting
- The draining effect of the EDZ has been investigated for maximum 5 bar hydrostatic water pressure
- In areas with a water ingress > 5 litres per minute per 100 metres tunnel, pre-excavation grouting should be performed to reduce the conductivity in the rock mass outside of the EDZ.

Most Norwegian tunnelling projects are based on rock support practice in hard rock with self-bearing capacity. This enables the use of rock reinforcement based on sprayed concrete in combination with rock bolts. Furthermore, PEG is a routine procedure in all tunnels excavated with drilling and blasting in Norway.

6 CONCLUSIONS

The permanent rock support based on sprayed concrete and rock bolts in Scandinavian practice is a proven approach for several decades. However, the current practice for final inner linings is unable to meet modern demands for sustainability. The presented concept enables a more sustainable solution regarding cost, excavated volume, construction time and CO_2 emissions. Utilization of effects from the excavation damage zone from blasting and permanent rock support combined with a watertight sprayed concrete would give a significant reduction in cement consumption, CO_2 emissions and amount of excavated rock in tunnels. Consequently, this would lead to reduced costs and excavation time. The SUPERCON research project has demonstrated several significant possibilities to reach the goal of constructing waterproof tunnel linings which are entirely based on sprayed concrete. The final results from the SUPERCON project are yet to come, and hopefully the results from the project could contribute to more effective tunneling with less CO_2 emissions.

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