MATERIAL TECHNOLOGY AND SPRAY-APPLICATION DEVELOPMENT FOR WATERPROOF AND DURABLE SPRAYED CONCRETE LININGS. GOALS AND BACKGROUND FOR THE SUPERCON RESEARCH PROJECT, NORWAY

ENTWICKLUNG DER MATERIALTECHNOLOGIE UND SPRITZ-APPLIKATION FÜR WASSERDICHTE UND NACHHALTIGE SPRITZBETONGEWÖLBE. ZIELE UND HINTERGRUND DES SUPERCON FORSCHUNGSPROJEKTS, NORWEGEN

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A number of countries now favour sprayed concrete for permanent ground support in tunnels. However, the use of sprayed concrete for final inner linings on a large scale has yet to be realized. An important shortcoming of the sprayed concrete technology is related to cracking caused by shrinkage, which in turn is the main obstacle for the construction of final inner linings entirely based on sprayed concrete. The SUPERCON research project aims to use new knowledge to reduce shrinkage, increase the ductility of the concrete, as well as improving the application process to enable waterproof final linings based entirely on sprayed concrete.

In vielen Ländern wird aktuell Spritzbeton als permanente und dauerhafte Ausbruchsicherung im Tunnelbau eingesetzt. Die Anwendung als endgültiges Innengewölbe in großem Umfang ist aber noch nicht realisiert worden. Ein wichtiger Mangel ist die durch Schwinden verursachte Rissbildung, welche das größte Hindernis für den Einsatz als permanente Innenschale darstellt. Das SUPERCON Forschungsprojekt zielt darauf ab durch neue Erkenntnisse bezüglich der Schwindenreduktion, durch erhöhte Duktilität und verbesserte Spritz-Applikation, den Bau von wasserdichten Innengewölben völlig basierend auf Spritzbeton zu ermöglichen.

1. Introduction

The present paper reviews the background and current status of the SUPERCON (acronym for Sprayed sUstainable PErmanent Robotized CONcrete) research program, currently carried out at the research foundation SINTEF and The Norwegian Geotechnical Institute NGI, in cooperation with The Norwegian University of Science and Technology (NTNU), all located in Trondheim.

The current state and last experiences with permanent sprayed concrete and its application in hard rock conditions are reviewed. Special focus is given to sprayed concrete as a permanent material being functional both for rock support and final inner lining.

The use of sprayed concrete for a final inner lining is challenged and limited by the required functionality for such a permanent waterproofing concept. Some technical experiences on how this challenge has been approached are reviewed with emphasis on the sprayed applied membrane method to seal and bridge the cracks in the rock support sprayed concrete lining.

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 approach of the SUPERCON project from a functional perspective for final inner linings in tunnels and caverns, originates from the documented system properties of undrained and partly drained waterproof sprayed concrete linings, waterproofed with bonded sprayed applied membranes.

In order to create a more robust technical solution, which still utilizes a sprayed concrete as the main lining structure, the emphasis of the SUPERCON project is to resolve the shortcomings which currently disqualifies sprayed concrete for use as the final inner lining. The goal is to increase the knowledge of sprayed concrete significantly. Hence several areas of use can be materialized.

On this basis, the paper addresses the technical goals for the planned material development of sprayed concrete within the context of the SUPERCON project. The main material composition improvements of the concrete, and further development of the robotized sprayed application process are outlined.

Finally, the environmental benefits of achieving a permanent functional sprayed concrete based inner lining is discussed and compared to other lining systems which are frequently in use today.

2. Technical background: Experiences and current practice sprayed concrete for permanent ground support

The hard rock ground support philosophy which has been implemented in the Scandinavian countries considers the rock mass as the main structural 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. 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. Loads such as bending or tensile stresses have been the normal case in hard rock ground. For this reason, the toughness of the sprayed concrete is a decisive strength parameter, leading to the use of fiber reinforcement. A significant part of the lining will under such conditions be a mechanically passive structure. Therefore, low thicknesses of sprayed concrete, as low as 50 mm minimum thickness were applied as the normal thickness. In areas with more pronounced blockiness, with 2 or 3 persistent joint sets, thicknesses in the range 80-100 mm were applied. In weakness zones sprayed concrete thickness up to 250 – 300 mm in the context of rib reinforcement have been applied.

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. For subsea road tunnels and the exposure to saline (ground)water, the minimum required thickness is 100 mm.

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 todays 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 [1] has also demonstrated that the intact sprayed concrete material, when constructed according to strict material requirements [2], 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.

2.1 Current practice for final lining in Norwegian traffic tunnels

Sprayed concrete has been used for permanent rock support in hard rock ground conditions approximately 4 decades. The main experienced shortcoming of sprayed concrete from the perspective of a permanent lining function, is that a lining based on pure sprayed concrete will exhibit seepages unless a special waterproofing measure is used. The seepages are caused by cracks in the sprayed concrete, mainly caused by shrinkage.

The main functional requirements for final linings in modern traffic tunnels relate to:

- Waterproofing, no water dripping in the traffic area
- Esthetical appearance
- Reduce the exposure of installations to corrosive environment
- Feasibility of anchoring bolts for different installations such as power lines, lighting, utilities
- Resistance to freeze-thaw cycles and resistance to formation of ice in the tunnel
- Stricter waterproofing requirement in the freezing zone of the tunnel: moist spots are normally not allowed

This leads to the need for a permanent inner lining of the tunnel. The traditional method in Norway has been to install a separate inner lining which functions as a water and frost protection system. Several versions of this have been used. The latest adopted version consists of precast elements and is installed as a separate structure. This is in principle an umbrella waterproofing, which collects the seeping water from the rock mass to be drained behind the water and frost protection system and led to the invert. Today's main concept of this lining system was developed in the end 1990's proved to be a very cost-effective solution at the time [2].

The concept of the traditional Norwegian water and frost protection system is illustrated in figures 1 and 2. This lining system has no structural interface with the rock mass and its reinforcement but takes for granted that the rock is stable with no long-term deformations. A potential positive contribution to the rock mass stability from this system is not accounted for when designing and installing the rock reinforcement.

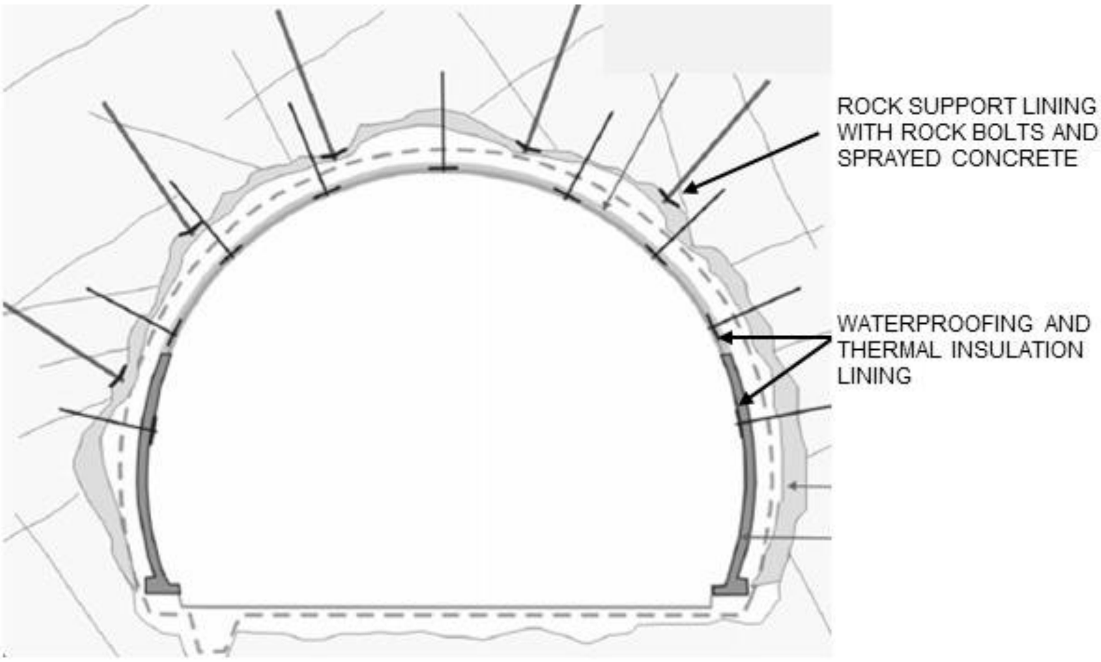

Figure 1: Principal layout of the lining design for traffic tunnels in Norway, with the two functional parts: the rock support lining and the water and frost protection lining. Modified after Broch et al [3]

Figure 2: Modern road tunnel design in Norway. Left: illustration of the lining systems rock support and final inner linings. Right: Photo of the interior with final inner lining, the version based on precast segments, for water and frost protection [4].

Figure 3: In-service condition of a section of the Holmestrand railroad tunnel in Norway after three years of operation after the completed construction (2016). The lining system is permanent sprayed concrete waterproofed with a spray applied membrane in a continuously bonded structure (photo: Karl Gunnar Holter).

Concerns about durability have been raised for these water and frost protection systems. A service lifetime of approximately 50 years has been assessed whereafter a complete replacement of the inner lining is foreseen. Therefore, several railroad tunnel projects built after 2013 have been constructed adopting the central European tradition, namely cast-in-place concrete linings and concrete pre-cast segment linings with backfilling in TBM excavated tunnels [5], [4] and [6].

A few successful attempts to waterproof sprayed concrete linings with spray-applied bonded membranes have been realized in Norway, namely the Gevingås and Holmestrand railroad tunnels. This method eliminates entirely the use of cast-in-place concrete or precast segments, and even any other inner lining system for water and frost protection. A photo from the Holmestrand rail tunnel after completion is shown in figure 3.

The function and properties of this system are discussed in section 4. These considerations, among others, form the basis for the technical goals and ambitions of the SUPERCON project.

2.2 Mix design and requirements for sprayed concrete for rock support

The specific material requirements and an example of a corresponding mix design for sprayed concrete in permanent rock support in Norway are shown in tables 1 and 2 next page.

Tab. 1: Typically required material properties for sprayed concrete for permanent rock support in hard rock [7]

Material property	Typical requirement	Achieved with	Applicable standard	Remark
Early strength	Upper J2	Middle to upper J2	NCA, 2011	Derived from Austrian Guideline
Final strength, 28 days	B35	60-70 MPa	NCA, 2011	Overperformance due to early age toughness requirement
Toughness measured as energy absorption on round panels	700J or 1000 J depending on required class	Normally slightly below	NCA, 2011	Slightly below is tolerated
Tensile bond to rock surface	No delamination	Application process, mix design	NCA, 2011	
Durability	Durability class M45, thickness > 80 mm. Durability class M40, thickness > 100 mm for subsea applications	Water/binder ratio < 0,45, respectively < 0,4 thickness for M45 and M40 durability classes	NCA, 2011	Results in extremely low conductive permeability, and high capillary porosities
Robustness of fresh mix for application	Pumpable, sprayable, remains on rock wall. Low rebound	High cement paste content, concrete temperature >20 °C	NCA, 2011	

Tab. 2: Mix design for sprayed concrete for permanent rock support from the Gevingås rail tunnel constructed 2009-2011

Component	Details	Amount, kg/m³	Remark
Cement	CEM II 42,5 A-V	510	Flyash cement
Pozzolanic binder	Silica fume	21	
Water	Water / binder ratio: 0,44		Including water added at the nozzle with the set accelerator
Aggregate	0 – 4 mm	340	Crushed
Aggregate	0 – 10 mm	1250	Natural
Fibres	Structural macro polypropylene	6	Requirement: energy absorption 1000J requirement according to NCA 2011

The sprayed concrete design relating to the requirements above meets the required functionality and durability for permanent rock support purpose in traffic tunnels. However, for such tunnels the cracking of the sprayed concrete which takes place during curing hinders the use of sprayed concrete as a final lining.

The functional requirement of a dry tunnel therefore imposes the need for a water protection measure in addition to the sprayed concrete itself. SUPERCON aims to develop sprayed concrete to such extent that an additional water protection measure is no longer needed.

3. Shrinkage and cracking of sprayed concrete

Cracking of sprayed concrete can have a number of causes. In the context of this study, cracking is caused by the behaviour of concrete itself and relates mainly to the different ways of shrinkage. This will be the main focus here.

Autogenous shrinkage measured on comparable sprayed concrete mixes in Sweden [7] suggests 0,4 – 0.5 mm/m unrestrained shrinkage. Measurements of autogenous and drying out shrinkage were carried out in the SUPERCON project on sprayed concrete with 7% dosage of alkali free accelerator. Unrestrained autogenous shrinkage was measured to approximately 0,4 mm/m with a total equivalent binder content of 510 kg/m^3 and a water/binder ratio of 0,45. The shrinkage caused by drying can be significantly higher than autogenous shrinkage, depending on the exposure of the concrete surfaces to the climatic conditions. Controlled measurements of unrestrained drying out shrinkage measured continuously, starting immediately after spraying indicated values around 1 mm/m measured on 150 mm thick slabs, with exposure to relative air humidity of 50% and storage temperature 23^{o}C.

The brittle behaviour of concrete in hardened condition with such magnitudes of shrinkage behaviour will cause cracking. The mechanical property of concrete, which is realistic to be considered in this context, is the failure strain in uniaxial tension. Normal values for failure strain of concrete in uniaxial tension are in the magnitude of 0,15 mm/m. Hence, the tensile deformation caused by shrinkage exceeds the failure strain with a factor of approximately 4.

Several attempts to assess the in-situ cracking of sprayed concrete in rock support linings were carried out during research in Norway in the period 2013-2014 [1]. Some findings are illustrated in figures 4 and 5.

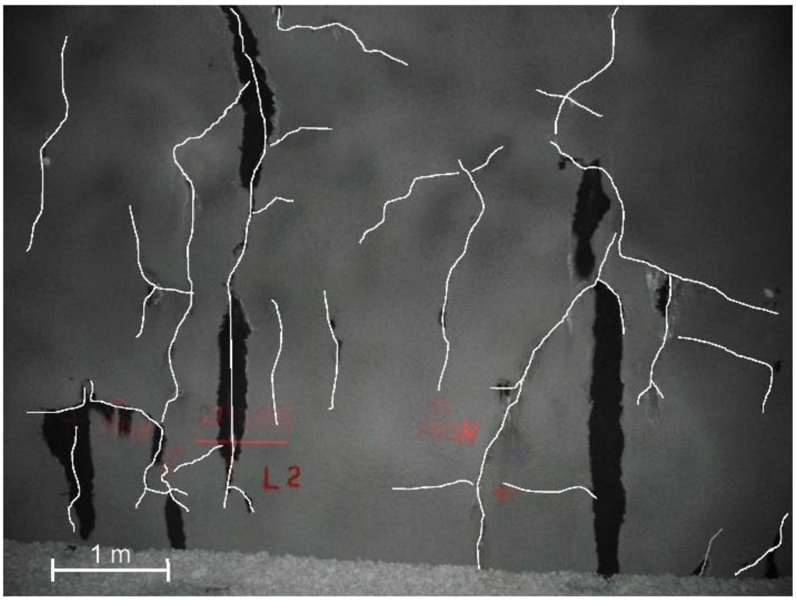

Figure 4a: Mapping and assessment of in-situ cracking of rock support sprayed concrete in hard rock. Observed and measured cracks are highlighted with white lines. Example from the monitoring and research section of the Gevingås railroad tunnel, Norway [1]

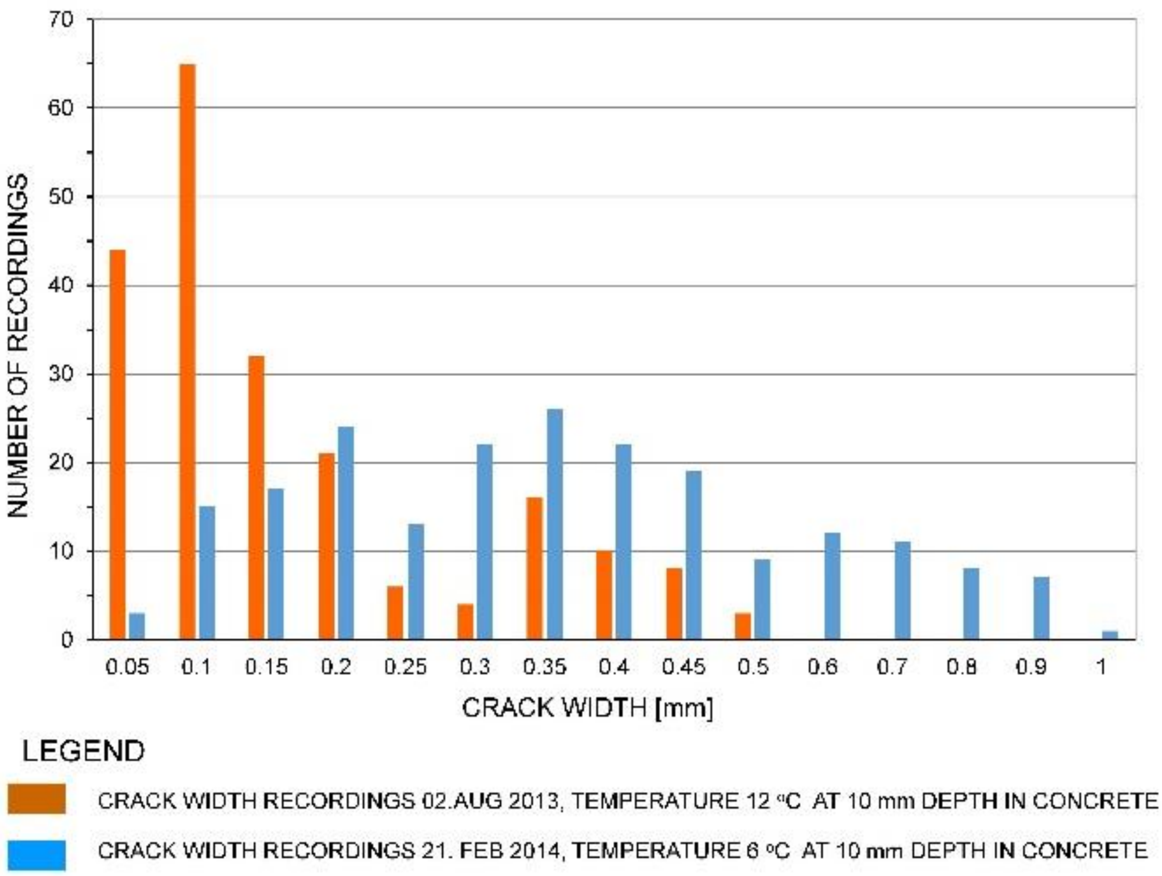

Figure 4b: Mapping and assessment of in-situ cracking of rock support sprayed concrete in hard rock. Observed and measured cracks are highlighted with white lines. Example from the monitoring and research section of the Gevingås railroad tunnel, Norway [1]

The observed cracking of the fibre reinforced sprayed concrete has not caused significant concerns for the rock support functionality of the lining in short term, unless the cracking is caused by a deforming rock mass. Cracking caused by deforming rock masses has been documented in a few cases, such as the Oslofjord and Lærdal road tunnels. However, such cases have been rare and exceptional in Norway.

Cracks represent potential seepage channels for water and hence create a need for the water protection to be installed in the tunnel. In a long-term perspective, seeping cracks in the sprayed concrete can potentially result in leaching of the binder matrix and hence a degradation of the sprayed concrete material and reduce the durability properties.

The occurrence of cracks can be seen in the photo in figure 4a and the left photo in figure 5. Crack apertures were measured with a measuring gauge, figure 5 right. This gave a classification of crack widths with a resolution in the range of 0,05 - 0,1 mm.

An example of crack width data is shown in figure 4b, the photo 4a shows the cracking situation which was investigated. The obtained data for crack widths are shown in the Figure 4b. The same cracks at the precisely same location were measured in August and February.

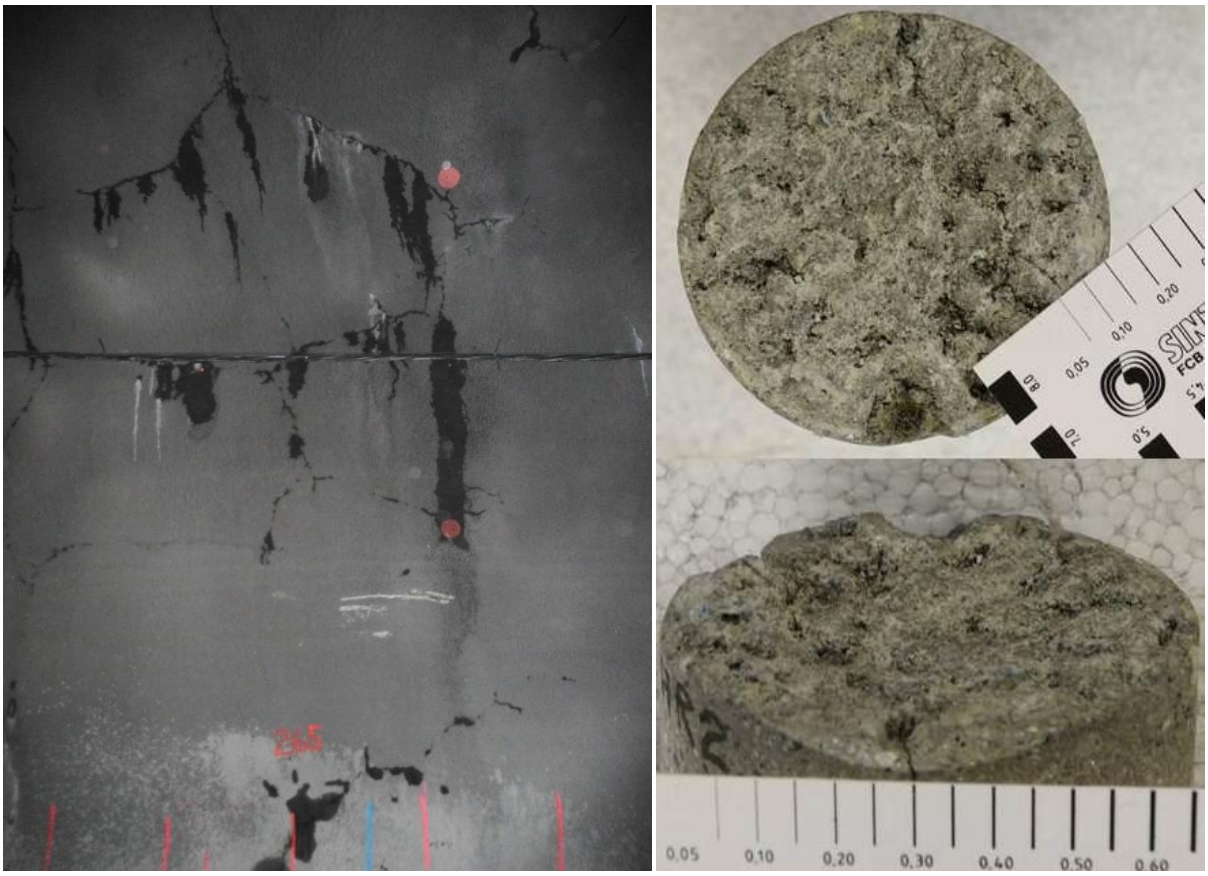

Figure 5: Left photo: Cracking of sprayed concrete visible as dark lines from water ingress, in rock support sprayed concrete in the research section of the Ulvin access tunnel. The red lines in the lower part indicate 1 m spacing. Right: Detailed crack images showing the use of a crack measuring gauge on a sprayed concrete sample from the rock support lining in the Gevingås rail tunnel. The core diameter is 76 mm [1]

Two important findings follow from these investigations:

- Crack widths have been measured in a range from 0,05 to 1 mm with the main portion of the cracks in the range from 0,1 to 0,4 mm.
- Thermal fluctuations in the tunnel result in thermal contraction and expansion of the rock and concrete materials.

The results from one measured section (figure 4, lower graphic) suggest a thermally induced shift of the measured crack width distribution. The measured crack widths show a larger number of crack widths in the range of 0.1 to 0.2 mm for the measurements in August, whereas the range 0,2 to 0.4 mm is more represented for the measurements in February. A temperature difference of 6 ^{o}C was measured at 100 mm depth in the lining between the two crack aperture data series. This corresponds to a measured difference of approximately 12^{o}C in the tunnel air between the warm season (August) and the cold season (February).

This documented scenario constitutes an important loading mechanism for final inner linings which are based on bonding between layers of different materials.

4. Objectives of SUPERCON: sprayed concrete as a permanent and final lining in infrastructure tunnels

The main objectives of SUPERCON were established having the following two main issues in mind:

- Existing knowledge with the technical shortcomings of the state-of-the-art sprayed concrete technology, and limitation in areas of use for final functional inner linings in tunnels.
- The significant potential in total financial savings and totally reduced carbon footprint for tunnel construction.

A conceptual lining model was established based on existing experience with the shortcomings, and recent technical development as to how to overcome these. Essentially this means to resolve the cracking challenge in a manner which is technical and financially viable. The approach which has been chosen is to base the research work on existing sprayed concrete practice, improve the material composition and application methodology, and importantly develop a sprayed concrete structure with thickness and properties which can be applied in the tunnelling industry with significant financial and environmental savings.

4.1 The sprayed membrane approach to waterproofing of a sprayed concrete lining

This approach resolved the leaking crack challenge by applying a bonded waterproofing membrane which seals the cracks. This is illustrated in figure 6.

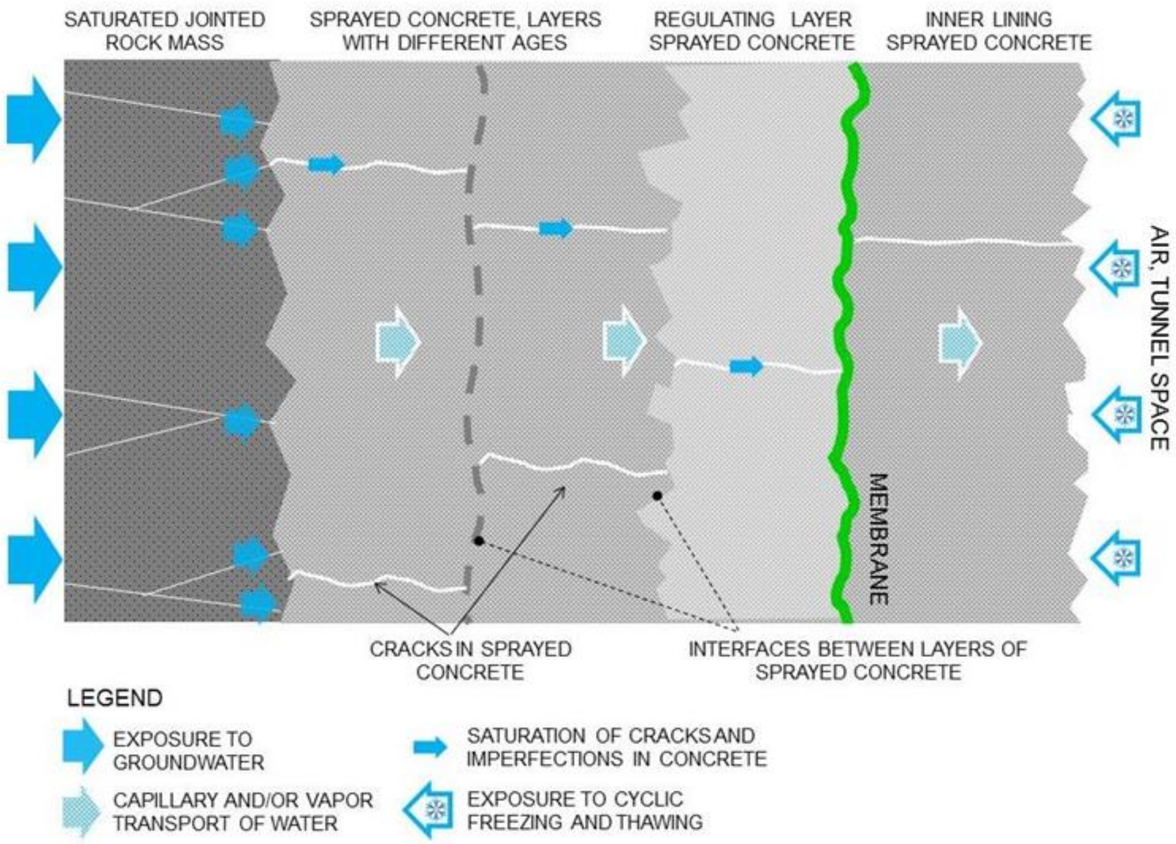

Figure 6: Cross section with details and waterproofing function for a tunnel lining with sprayed concrete in combination with a spray-applied membrane [1]

The waterproofing function and the structural integrity of the sprayed membrane in Figure 6 can be summarized in three main points:

- Bridging of cracks to stop the water flow through the conductive cracks in the concrete
- Allowing a certain amount of water to pass in the form of water vapor
- Maintaining sufficient in-situ tensile bonding strength under the exposure to water at cracks as well as the vapor exposure through the capillary pores.

The two important material properties of the membrane can therefore be summarized:

- Sufficient elasticity to seal and bridge the deformation across the concrete cracks without rupture
- Sufficiently high water vapor permeability
- favourable hydroscopic water absorption properties in combination with the required tensile strength at realistic moisture contents.

The experienced shortcomings of this approach have been related to constructability issues, particularly the robustness of the application methodology in a tunnel construction context.

4.2 The SUPERCON approach to waterproofing of a sprayed concrete lining

The conceptual model for the SUPERCON approach was derived from the model for a sprayed concrete lining with waterproofing with a spray-applied membrane, outlined in section 4.1. Hence, the target properties for the improved sprayed concrete material in the SUPERCON project can be conceived in a corresponding section, shown in figure 7.

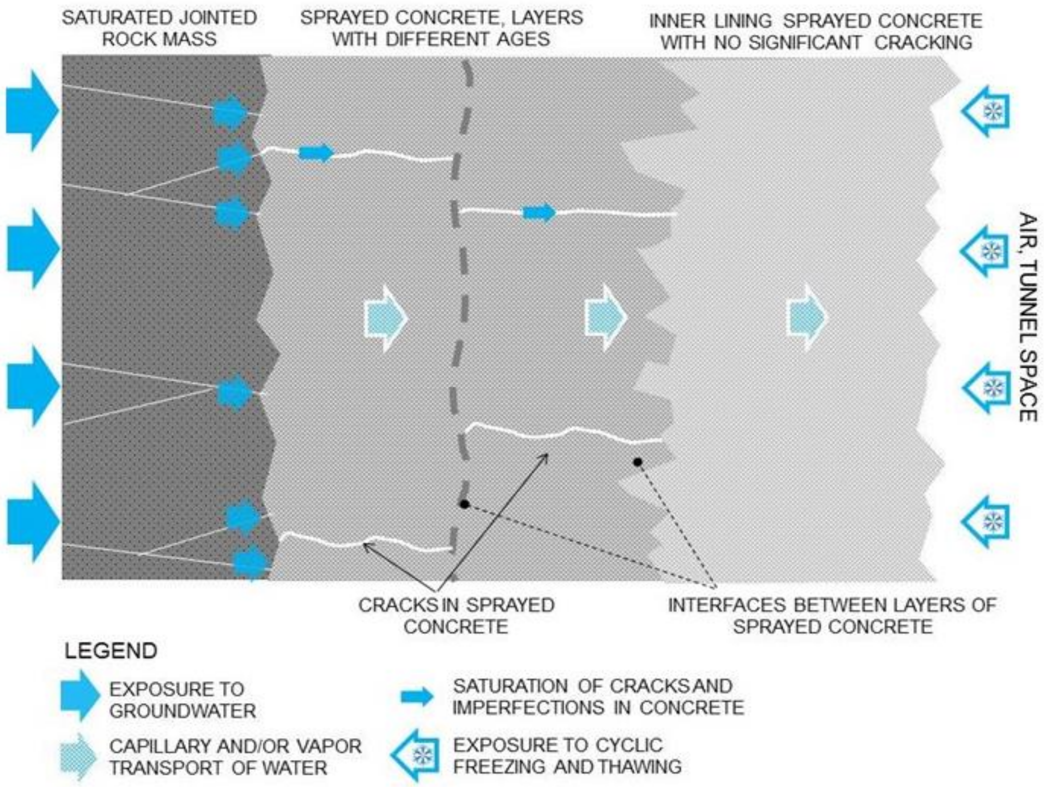

Figure 7: Cross section of lining details with the main intended area of use for the sprayed concrete technology in the SUPERCON project: a functional waterproof layer based on sprayed concrete to be applied onto the rock support lining

The decisive load for the improved waterproof sprayed concrete in the SUPERCON project is the opening and closing of cracks in the substrate of rock support sprayed concrete. This is illustrated in the loading model, shown in figure 8.

The main function of the new sprayed concrete is therefore to accommodate this load without causing cracking. Consequently, the important objective of the SUPERCON sprayed concrete is develop properties assigned for an in-situ applied concrete material which after hardening exhibits sufficient deformability and crack distribution. Eventual occurring cracks should be in the microfissure range with crack aperture lower than 0,1 mm.

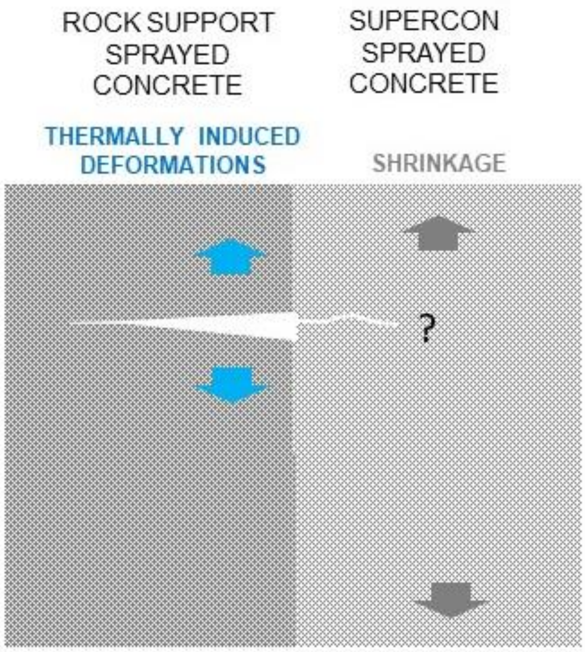

Figure 8: Loading model for the deformation exposure at cracks in the rock support sprayed concrete lining

Fluctuations and changes in the moisture content in the concrete represent a source for shrinkage effects and hence should be considered a load imposed on the lining. A thorough investigation of the moisture condition in several sprayed concrete linings was carried out in Norway [5]. The linings which were investigated were all continuously bonded from the rock substrate throughout the lining, and hence had no draining components. The moisture contents across the linings were measured, together with the hygroscopic sorptivity properties of the materials.

On this basis a moisture content model was established. This model is shown in figure 9 with the moisture content which was measured at the driest time of the year in the tunnel, namely the winter season. The results were used to assess the risk of freezing damage in the concrete material at low temperatures. This model will also be used to assess the maximum amplitude in relative humidity in the concrete in the part of the lining closes to the lining surface and in turn be used to analyse the magnitude and range of possible shrinkage caused by the humidity fluctuations at the critical points in the lining. The apparent small influence of the membrane is accredited to the vapor permeability of the membrane, which was found to be in the same order of magnitude as the concrete.

The target properties of the SUPERCON sprayed concrete needs to fit into a functional model for moisture transport and moisture content. This is particularly important in the case of a bonded and undrained lining structure, in which the concrete interacts with the rock mass in terms of water transport and absorption. The findings on this topic from research in Norway 2011-2015 [1] will serve as a basis for further work.

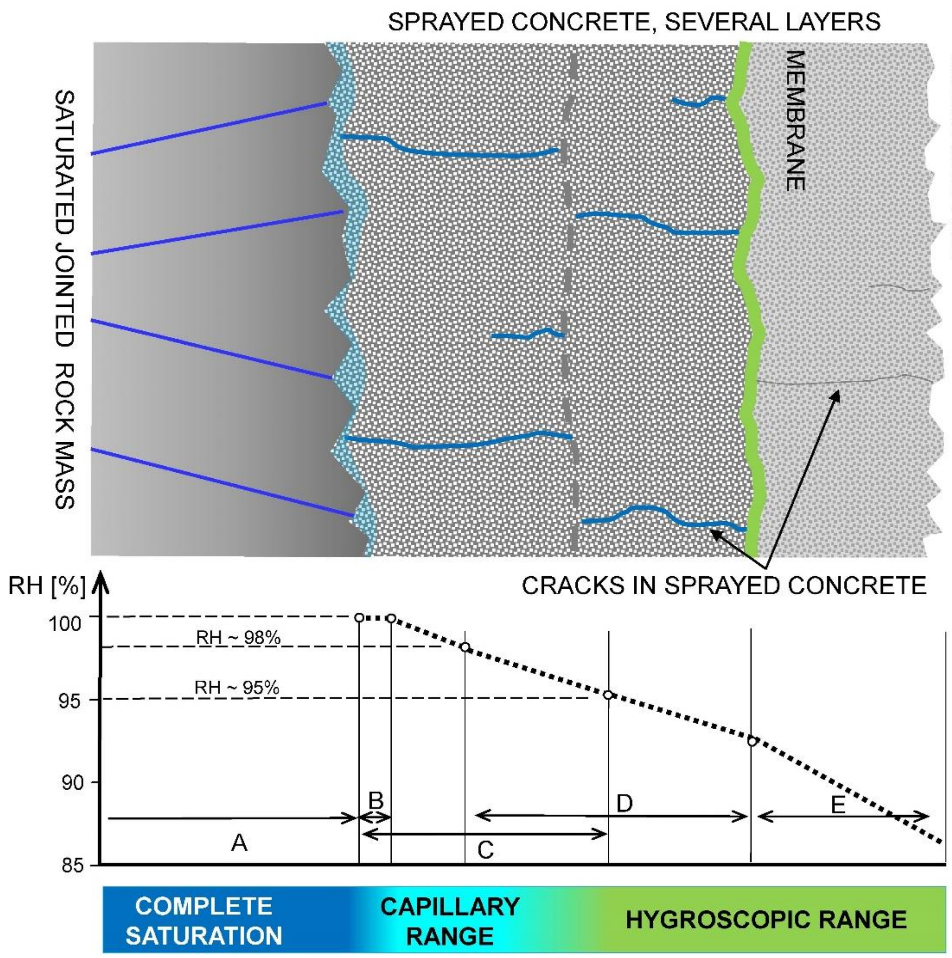

Figure 9: Principal model for moisture condition in an undrained and bonded lining structure given as relative humidity (RH) and moisture transport mechanisms [5].

The different moisture transportation mechanisms shown in figure 9 are the following:

A: Conductive water flow in rock fractures

B: Conductive water flow in rock fractures

C: Conductive water flow on cracks in concrete and capillary transport in concrete

D: Conductive water flow on cracks in concrete and vapor transport in concrete

E: Vapor transport in membrane and concrete

5. Specific targets for the SUPERCON technology development

5.1 Material composition and material property targets

The main target of achieving a waterproof sprayed concrete in-situ on the tunnel surface has been oriented towards significantly reducing the formation of cracks caused by the different sources of shrinkage.

Completely eliminating shrinkage is not a realistic goal, when utilizing hydraulic binders. Hence, a certain remaining amount of shrinkage and consequently a source of cracking must be accounted for. The following three sub-targets have been defined for the material development process:

- Reduce shrinkage and control the extent of shrinkage in length and distribution
- Increase the ductility of the concrete in hardened condition
- Crack control: significant reduction of crack widths, target range 0,02 – 0,05 mm, maximum 0,1 mm

These sub-targets are illustrated in figure 10.

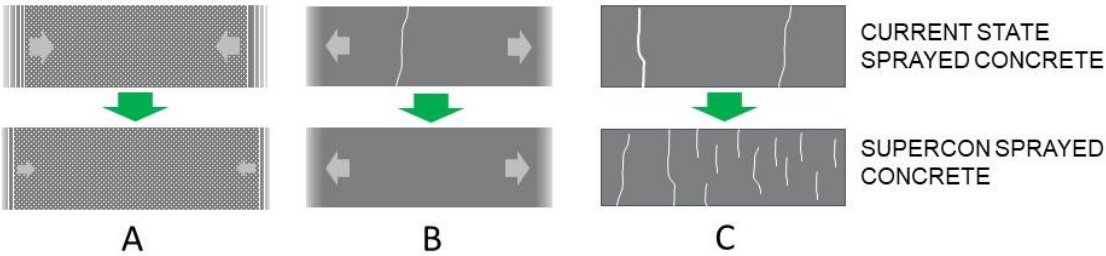

Figure 10: Three important sub-targets of material technology development for the SUPERCON project. A: significant reduction of shrinkage. B: significant increase in ductility represented failure strain in uniaxial tension. C: significant distribution of cracks in concrete with the use of fibre technology

These targets are considered by SUPERCON as measurable parameters based on the physical understanding shrinkage and cracking substantiated by the measurements explained in section 4. The main specific methods are listed in table 3. The technology within each of these methods represent already existing or recent technology developments which have taken place in the concrete industry. The aim of the research within SUPERCON is to utilize these improvements in the concrete technology with the purpose of improving sprayed concrete.

Tab. 3: Specific areas of technical performance which form the technical goals for the SUPERCON project

Performance parameter	Today's state of technology	SUPERCON target	Method, remarks
Shrinkage [mm/m]	Autogenous: 0.5 Drying out: 1	Autogenous: 0.2 Drying out: 0.3	Reduced binder content Use of flyash and lime Hydration accelerator
Ductility, Failure strain in uniaxial tension [mm/m]	0,15	0,3	Use of polymers in base concrete mix
Crack distribution, Maximum crack aperture	Typical range 0.05 – 0.6 mm	Typical range 0.02 – 0.05 mm, maximum 0.1 mm	Use of fibres to achieve strain hardening properties
Hydraulic conductivity of intact concrete material	10^{-14} m/s and lower	10^{-14} m/s	Maintain at least same performance as today's sprayed concrete
Vapor permeability of intact concrete material	Range: 1 - 2 $\cdot 10^{-12}$ kg/m·s·Pa	Range: 1 -2 $\cdot 10^{-12}$ kg/m·s·Pa	Maintain at least same performance as today's sprayed concrete

A significant reduction of the cementitious binder content is considered the most important and decisive success factor of achieving the main goal. A major part of the research work is therefore focusing on testing of alternative mix designs, materials and replacements for cementitious binders such as flyash and limestone powder.

5.2 Improved spray application process

Sprayed concrete is by nature produced as a spray application process, in which details such as nozzle distance, nozzle angle, concrete pumping flow rate, as well as air and concrete pumping pressures strongly influence the final in-situ material properties on the rock surface.

The parameters which exhibit the largest scatter and range are nozzle distance and nozzle angle. This is particularly the case in drill-and-blast excavated tunnels. This is illustrated in figure 11.

A separate working module on improved spray application will approach the challenge of achieving the most consistent application. This directly influences the quality of the compaction of the concrete on the rock surface. To achieve such application improvement extensive use of surface scanning for the verification of surface details and real-time guidance of the spraying nozzle is considered important.

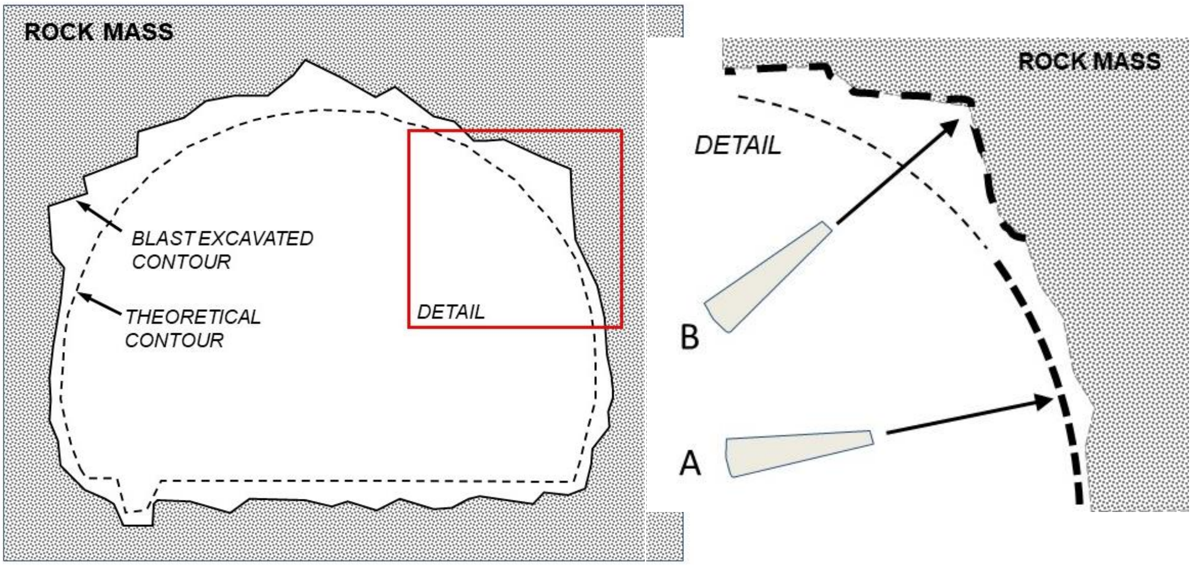

Figure 11: Application of sprayed concrete on a blast excavated rock surface. Detail A indicates ideal spray angle and nozzle distance with an even rock surface. Detail B illustrates the importance of the nozzle following the uneven rock surface in order to avoid severe inhomogeneities and poor compaction

6. Main benefits regarding environmental impact

According to Ecoinvent 3, based on [8] plain concrete with cement with 200 kg/m^3 CEM II/B approximately 88% of the CO_2-equivalents are from cement. To emphasise the environmental effect regarding the carbon footprint, it is chosen to present basic examples by only using the cement in the concrete. Hence, this perspective of this comparison of the environmental impact of the different types of tunnel linings is conservative.

Four types of recently used tunnel linings in Norwegian tunnels are presented in this approximation, presented in Table 4, as described in the following:

For lining type 1 (Cast-in-place) the following procedure is common during excavation with drilling and blasting; the first stage of the lining includes a layer of sprayed concrete to establish an initial rock support, followed by a levelling layer of sprayed concrete. The final layer of the lining is concrete casted using formwork.

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 [6].

Lining type 3 (Pre-cast concrete elements, Norwegian traditional system, figures 1 and 2) is typically used in road tunnels. The first stage of the lining includes a layer of sprayed concrete, to establish an initial and permanent rock support, followed by installation of pre-cast elements, where the annular space between the sprayed concrete for rock support purpose and the pre-cast elements remains open.

Lining type 4 (multi-layered sprayed concrete-based lining), SCL as proposed by the SUPERCON, illustrated in figure 7.

Tab. 4: Overview of composition and thickness of four different types of tunnel linings

Lining type	Description	CEM II/B [kg/m^3]	Thickness [m]
1	SC ground support	430	0.10
	SC levelling layer	430	0.30
	Cast-in-place concrete lining	400	0.60
2	Pre-cast segmental lining	400	0.40
	Backfill	350	0.20
3	SC ground support	430	0.10
	Pre-cast elements	400	0.20
4	SCL	430	0.15

According to Ecoinvent 3, based on [8] there are approximately 722 kg CO_2-equivalents per ton CEM II/B. The bar plot in figure 11, presents the calculated consumption of cement and CO_2-equivalents for the four different types of lining. Lining type 1 (Cast-in-place) is an extreme approach that requires 412 kg cement per m^2 tunnel lining which results in 297 kg CO_2-equivalents m^2 tunnel lining. Lining type 2 (Pre-cast segmental lining) requires 230 kg cement per m^2 tunnel lining which results in 166 kg CO_2-equivalents m^2 tunnel lining, which is 44% less use of cement and CO_2-equivalents than Lining type 1. Lining type 3 (Pre-cast elements) requires 123 kg cement per m^2 tunnel lining which results in 89 kg CO_2-equivalents m^2 tunnel lining, which is 70% less use of cement and CO_2-equivalents than Lining type 1. Lining type 4 (multi-functional layer of sprayed concrete) requires 65 kg cement per m^2 tunnel lining which results in 47 kg CO_2-equivalents m^2 tunnel lining, which is 84% less use of cement and CO_2-equivalents than Lining type 1.

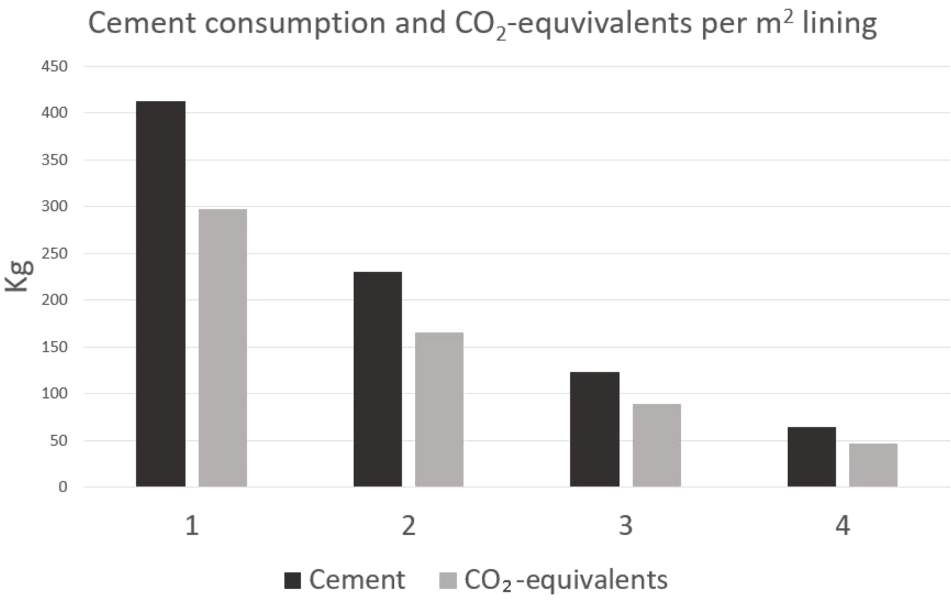

Figure 12: Cement consumption (CEM II/B) and associated CO_2-equvivalents per m^2 lining based solely on the cement content, for the four lining types presented in Table 4

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 considerably, and the same will also imply for construction costs and building time.

The Norwegian tunnelling method by using sprayed concrete as tunnel lining utilizes the capacity of the rock mass as a building material, to avoid expensive and time-consuming constructions with unnecessary use of resources and holds a great potential to secure a low CO_2-footprint when applied also as the final lining having improved water tightness.

7. Conclusions

With the current state-of-the-art sprayed concrete technology, it is possible to produce a high quality in-situ hardened material when applied properly. The intact sprayed material exhibits very low hydraulic permeabilities and favourable porosity properties from a durability perspective.

The in-situ cracking of the sprayed concrete structure on a rock substrate under realistic conditions in a tunnel poses the main obstacle for constructing a final inner lining entirely based on sprayed concrete unless a separate waterproofing measure is added.

Based on measurements of shrinkage and in-situ cracking of sprayed concrete, an array of technical targets for the material development of the SUPERCON research project have been formulated. The areas of technology relating to mix design which are pursued are the following:

- Binder technology for shrinkage reduction
- Polymer technology for increased ductility
- Fibre technology for crack distribution

These technologies are well known from other areas of concrete applications. An important goal of the SUPERCON project is to obtain increased knowledge within concrete technology which can be realised in the spray application situation, and hence increase the knowledge base for sprayed concrete.

Furthermore, extensive use of state-of-the art scanning technology and real-time computerized control of the nozzle angle and distance to the substrate are included in the research. The goal of this working module is to improve the consistency of the compaction of the sprayed concrete and hence reduce the inhomogeneities of in-situ applied concrete material.

Significantly increased use of sprayed concrete for final inner tunnel linings are expected resulting from the SUPERCON research. Considerable financial savings and reduced carbon footprint are expected.

ACKNOWLEDGEMENT

This paper/presentation is a part of the research project "**S**prayed s**U**stainable **PE**rmanent **R**obotized **CON**crete tunnel lining (SUPERCON)" financed by the Research Council of Norway (project no. 294724), in cooperation with industrial partners AMV, BASF, Bever Control, Bekaert, Elkem, Entreprenørservice, NORCEM, Unicon, SWECO Norge, Veidekke, Wacker Chemicals Norway. Research partners in SUPERCON are NGI, NTNU and SINTEF. The following project owners support the project; Bane NOR, Nye Veier and the Norwegian Public Roads Administration.

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