# Durability development in sprayed concrete for rock support; Is it possible to establish a basis for modelling?

P. Hagelia

Norwegian Public Roads Administration, Norway

Road Department, Tunnel, Geology and Concrete Division

**The Norwegian Public Roads Administration has investigated durability of sprayed concrete for rock reinforcement for almost three decades. The work involved core extraction, standard concrete testing, concrete petrography and chemical water analysis. The durability challenges are mainly related to a complex sulfate attack in sprayed concrete on sulfide-bearing Alum Shale and a combined biofilm- and abiotic attack in subsea sprayed concrete within the subsea environment. Both deterioration schemes have caused transformation of the cement paste matrix and localised destructive steel fiber corrosion where conditions are unfavourable. This paper investigates the possibility of establishing a basis for computer modelling in view of accumulated data from four main exposure situations. The emphasis was laid on the complex interactions of water loads, geological loads and design parameters such as concrete mixes and spray thicknesses. Due to the typical complex and uneven distribution of both exposure conditions and degradation phenomena, being very dependent on site-specific characteristics, durability modelling of sprayed concrete for rock support seems to be an extremely difficult task. Collection of empirical data over several years is a prerequisite for building a fundamental basis for computer modelling.**

***Key words: Sprayed concrete, durability development, water environment, geological context, design, modelling versus empirical approach***

## 1 Introduction

Modelling of concrete service life by the aid of computers is an attractive approach, which may be used as a tool for estimating times of interventions and calculation of final lifetimes [Breugel et al., 2008, Li, 2016, Wegen et al., 2012]. Aging of structures represents a very important issue, having a very significant impact on modern society. However, investigations into the problem of aging require both a scientific and a practical approach

[Breugel, 2017]. Computer models for such purposes must incorporate essential features of concrete degradation mechanisms, the impact of reaction progress on strength and structural integrity in different concrete materials over time and overcome the traditional barrier between technical and economic disciplines. It is implicit that development of such models needs to be verified by empirical data from real life situations.

Hitherto, most computer models have been developed for specific purposes, such as single deterioration mechanisms (carbonation, acid attack etc.) or structural mechanical performance at different levels. However, integrated models accounting for scale dependent properties have also been established, for example the Lattice fracture model of TU-Delft [Schlangen & Garboczi, 1997]. Further developments have attempted to incorporate mechanisms both at microscale, mesoscale and into structural scales. Yet, successful models are mainly applicable to cast concrete structures. Sprayed concrete used for rock support in tunnels is much more complex with respect to both material properties and exposure conditions. To the present authors knowledge, no tool exists for modelling durability of sprayed concrete. The main objectives of this paper were to:

1) Establish the main differences between sprayed concrete and cast concrete structures, their characteristics and contrasting exposure situations.

2) Investigate the requirements for modelling sprayed concrete durability development in view of accumulated data.

## 2 Characteristics of sprayed concrete and exposure environments

### *2.1* ***Background***

Rock reinforcement in Norwegian tunnels is based on fiber reinforced sprayed concrete and rock bolts. In the most unstable rock masses, reinforced sprayed concrete ribs are employed. The engineering classification for rock masses and the design of rock support is based on rock mass rating according to the Q-system invented by Barton and co-workers [Barton, et al. 2004]. The rock reinforcement is designed for 100 years' service life. However, presently we have only about 25 years of experience regarding durability of modern wet-sprayed concrete technology.

Previous durability studies suggested that the sprayed concretes in all environments were sound, only with marginal effects of carbonation. However, sprayed concretes in subsea tunnels were showing some steel fiber corrosion in thin layers due to chloride penetration. Most subsea tunnels were then young (about 4-10 years) and it was advised to follow up the further development [Davik, 1997, 1998]. Later studies showed that some sprayed concrete in the Alum shale and subsea environments had suffered some deterioration after 5-10 years in service [Hagelia et al., 2003; Hagelia, 2011; Holm, 2011a,b]. Recent work within the R & D Programme Durable Structures confirmed that degradations were continuing at certain locations in the Alum shale and subsea environments. However, most of the sprayed concrete in these aggressive environments was still mainly sound after up to

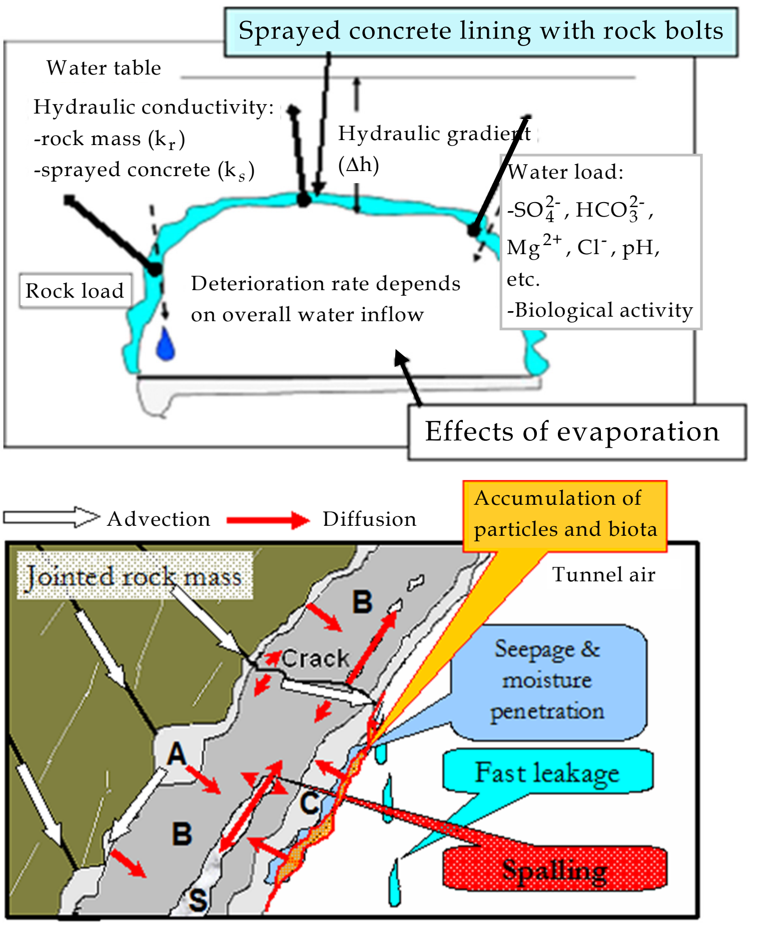


*Figure 1: Top: The main environmental loads acting on sprayed concrete for rock support in tunnels. Bottom: Schematic cross-section through rock mass and sprayed concrete (right). Degradations adjacent to the rock mass (Zone A) and outer concrete (Zone C) at the expense of sound concrete (Zone B) may lead to spalling (S).*

around 25 years in service [Mannvit, 2016; Hagelia, 2018a,b]. The methods of investigations were following the suggestions of [Franzén et al., 2001].

Figure 1 illustrates the complex environmental loads acting on sprayed concrete in the tunnel environment. In aggressive environments, the attacks mainly influence the concrete adjacent to leaking joints in the rock mass and permeable adhesion zones (Zone A) and within the surface region (Zone C) if leakage water is present. Surface attacks mainly occur in presence of small and widespread aggressive leakages, whilst single larger leakages on discrete cracks through concrete are less significant. Spalling (S) may take place along the adhesion zone or within the sprayed concrete layer.

The occurrence of degrading and intact domains of sprayed concrete is closely associated with presence and absence of water leakages, respectively, being distributed in a very scattered fashion (Figure 2). Dry or slightly moist sprayed concrete domains show few if any signs of deep degradations within Zone C, being mainly affected by surface carbonation [Hagelia, 2011, 2018a].

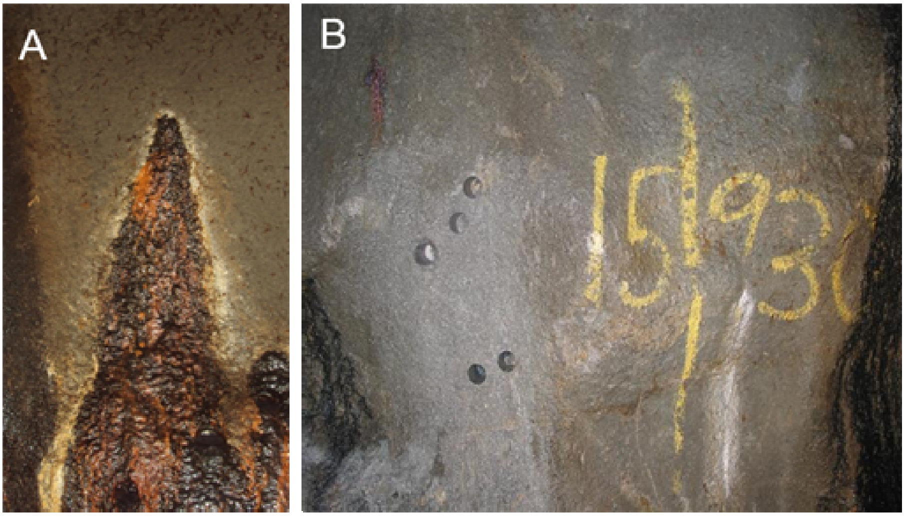


*Figure 2: Typical distribution of degradation phenomena in sprayed concrete. A: Quite dry unaffected areas and localised degradation associated with water load and biofilm (A). B: Moist surfaces with some focused leaching. Examples from subsea concrete.*

The context of sprayed concrete used for rock support in tunnels differs much from most cast concretes. Whilst cast concrete structures have smooth outer surfaces and most commonly have no direct contact with aggressive water, the sprayed concrete in tunnels represents a rough, tortuous and rather thin concrete layer sitting on an uneven rock substrate, which is partly influenced by leakage water. For example, sprayed concrete in subsea tunnels is to a great extent affected by saline ground waters, whose penetration is governed by both diffusion and water pressure, e.g. by the local hydrogeology [Hagelia, 2008, 2011, 2018a]. In contrast cast concrete structures, such as coastal bridges, are influenced by diffusion-controlled chloride penetration at hydrostatic conditions. Other differences between sprayed concrete and cast concrete are summarised in Table 1. The relatively higher level of drying shrinkage in sprayed concrete is a consequence of the use of setting accelerators. In contrast to plastic behaviour of cast concrete during hydration, much cement hydration continues when the sprayed concrete is already stiff. This results in a mode of porosity which is different from cast concrete, making the matrix more sensitive to water movements and enhanced effects of drying shrinkage [Lagerblad et al., 2010].

It is therefore obvious that the basis for establishing computer models for sprayed concrete durability development must account for a greater complexity than traditional approaches

*Table 1: Comparison of material characteristics of wet sprayed concrete and cast concrete*

| **Property** | **Wet sprayed** | **Cast concrete** | **Remark** |
|---|---|---|---|
| Water/binder ratios | (0.35) 0.40-0.55 | 0.35-0.55 | Common ranges |
| Aggregate grading (mm) | 0-16 | 0-25 | Common ranges |
| Binder contents | 380-500 kg/m$^3$ | 350-450 kg/m$^3$ | Common ranges |
| Silica fume or pozzolana | "Always" | Common | |
| Setting accelerator | Always used | Not common | Al-sulfate etc.. |
| Fibres | Very common | Less common | |
| Surface characteristics | Rough & tortuous | Plan and even | |
| Drying shrinkage | 0.8-1.2 vol-% | 0.4-0.6 Vol-% | Approximate |
| E-modulus, example | ≈ 22 GPa | ≈ 28 GPa | Approximate |
| Layering/inhomogeneity | Not uncommon | Less common | Air void structure |
| Rebound (of total vol.) | ≤ 5 vol-% | Irrelevant | Includes fibres |

used for modelling of cast concrete. Figure 3 gives a summary of the main ingredients, which must be incorporated into the design of models.

### 2.2 *Water loads*

Water loads acting directly on the sprayed concrete lining should be split into three terms, namely a) the chemical composition of the ambient ground water, b) the permeability of the adhesion zone (tight or open) and c) the effects of evaporation within tunnel space. The ground water composition may be classified according to the ranges given for Exposure classes in EN-206. It would, however, be better to use actual pH and ion concentrations together with additional variables such as bicarbonate concentrations and biofilm, which are not included in the concrete standard [Hagelia, 2008]. Permeable adhesion zones represent channels for ground water, which may reach somewhat large areas of sprayed concrete in contact with the rock mass. It has been demonstrated that aggressive waters in open adhesion zones lead to enhanced deterioration adjacent to the rock mass in Zone A. However, deposition of minerals in the contact zone may reduce the influence of ground water over time by blocking some of the open space, such as in subsea concrete.

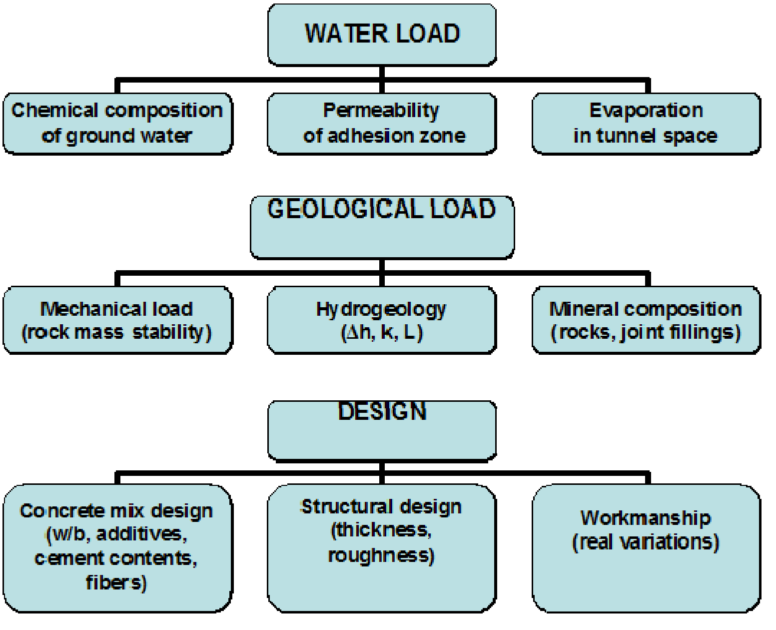


*Figure 3: The durability development of sprayed concrete is largely governed by complex variations and interactions of water loads, geological loads and design parameters*

Conversely, and notably in the black shale environment, a very low pH due to sulfide oxidation may lead to enhanced permeability in the adhesion zone, whilst in cases with excellent primary adhesion sulfide oxidation seems much inhibited (Figure 4) [Gulland, 2015; Hagelia, 2011, 2018a,b]. In cases where the sprayed concrete is exposed to leakage water in the tunnel space, draught from traffic and tunnel fans sometimes leads to increased ionic strength due to evaporation, i.e. being more aggressive than ambient ground water. Hypersaline waters have been reported from subsea tunnels [Hagelia, 2008]. Mechanical erosion by water is not very important in modern tunnels, because fast-running and volumetric large leakages are prevented by pre-grouting during construction.

### 2.3 *Geological loads*

The geological loads should be split into: a) mechanical loads due to rock mass stability, b) hydrogeology and c) mineral composition of rocks and joint fillings and their solubilities. Effects from an unstable rock mass may potentially lead to microcracking and an enhanced hydraulic conductivity of sprayed concrete linings, being higher than indicated by the w/b-ratio related primary shrinkage [Hoseini et al., 2009]. This may perhaps take place where the sprayed concrete thickness is insufficient with respect to local rock mass loads, likely at an early age before movements in the rock mass have "settled". The hydrogeological parameters; rock mass hydraulic conductivity (k), water pressure ($\Delta h$) and rock cover above tunnel (L) govern the tunnel leakages and their distribution. Rock joint frequencies may be used as proxy for hydraulic conductivity in representative elementary volumes and application of Darcy's law. However, at local scale water flow is governed by the properties of one or few single cracks where parallel plate theory or derivatives should be used. In some rock masses, such as black shales, the concentrations of iron sulfides represent a source for sulfuric acid and sulfate. Acidification may be severe in underground space within sulfide-bearing rock masses where the ground water level has dropped, forming vadose zones with oxygen saturated waters [Bastiansen et al., 1957]. However, systematic grouting in modern tunnel construction counters these effects. Dissolution and precipitation of rock joint materials may be soluble and hence influence the water leakage [Hagelia, 2011, 2018a]. In Norwegian subsea tunnels, the leakages are mostly reduced over time, due to clogging or precipitation [Davik, 1997].

### 2.4 *Design*

The concrete mix design and structural design (especially spray thickness) are key "resistance" parameters, which counter-weigh the effects of environmental loads. The

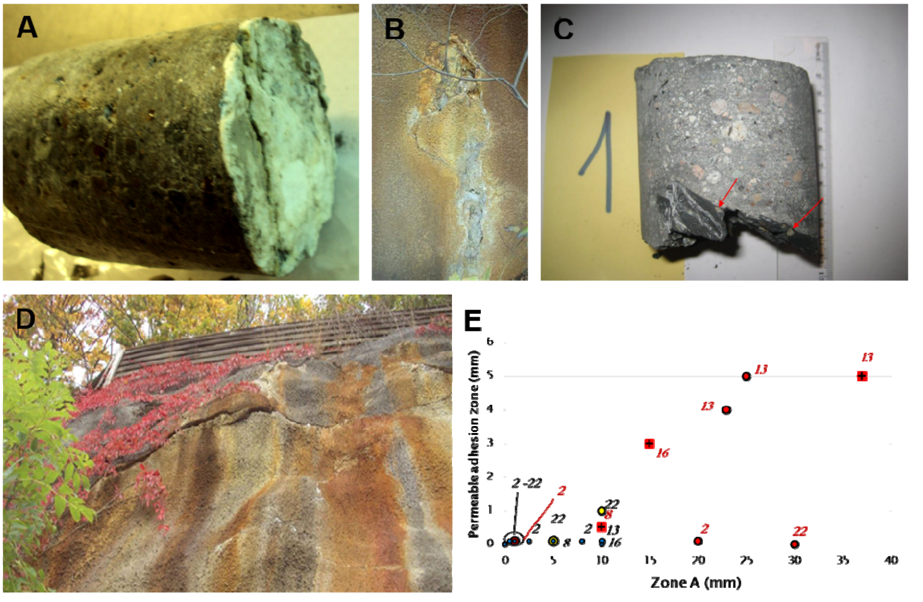


*Figure 4: Effects of adhesion properties. A: Subsea sprayed concrete with deposition of brucite & calcite (pH ~ 9-10) on permeable adhesion zone, may restrict further access of saline ground water (age 16 yrs). B: Sulfuric acid attack due to oxidation of iron sulfides in Alum shale, (pH ~ 2-4 evidenced by jarosite-bearing red rust) leads to increasing permeability along the adhesion zone, with strong dissolution and spalling of sprayed concrete (age 27 yrs). C: Excellent adhesion to Alum shale substrate with no sign of pyrite oxidation (arrows) and sulfuric acid attack [Gulland, 2015]. D: Severely cracked sprayed concrete on alum shale caused by thaumasite sulfate attack (TSA), popcorn calcite deposition (PCD), leaching and effects of sulfuric acid (age 27 yrs). E: The width of water permeable adhesion zones may enhance deterioration by TSA and PCD in sprayed concrete adjacent to Alum shale (Zone A) [Hagelia, 2018a,b]. Red squares = influence of sulfuric acid, red circles = influence by sulfate at neutral pH, yellow = slightly permeable adhesion zone, blue = apparent none-permeable adhesion zone. Numbers refer to concrete age at time of sampling.*

designed w/b-ratios, pozzolana (commonly silica fume), cement contents and capillary porosity puts constraints on the hydraulic conductivity of the material and resistance against aggressive waters. Likewise, the fiber type/contents, strength and energy absorption capacity provides information relevant to resistance against mechanical loads [Bjøntegaard et al, 2018]. The aggregates should also be characterised with respect to potential alkali aggregate susceptibility and sulfide contents. Sprayed concrete thickness variations have an influence on both water chemical and mechanical loads and likely also on oxygen gas permeability. Presently, a minimum thickness of 100 mm is specified for aggressive environments, whilst a minimum thickness of 80 mm is employed in the other environments. Finally, it should be kept in mind that the real design is ultimately determined by the workmanship and quality regime at each site. Variations regarding roughness, tortuosity and thickness are strongly influenced by the procedures of rock blasting and spraying operations and may be very difficult to document.

## 3 Durability results

Tunnel investigations and research in Norway has unveiled several deterioration mechanisms (Table 2). It should be emphasised that more than one degradation mechanism takes place at the same time and at different paces due to the complex interaction of water loads, geological loads and design parameters. The aggregates were inert [Hagelia, 2011, 2018; Holm 2011a,b; Mannvit, 2016].

The following environments were investigated and reported in the R&D programme Durable Structures, all of which represent experience up to about 25 years in service:

- Freshwater environment (XC2-XC4, XD1-XD3, X0)
- Mildly acidic environment (XC2, XD0, XA1)
- Alum Shale environment (XC2-XC4, XD0-XD3, XSA)
- Subsea environment (XC2-XC4, XD1-XD3, XS3, XA2-XA3)

XSA is defined in NS EN 206 for the specific problems related to sulfate and acid attack mainly encountered in Norwegian Alum shale environment. Identification of XSA conditions requires special treatment in each case, whilst the concrete mix should at least correspond to M40. It was difficult to assess the impact of mechanical loads due to inhomogeneities and lack of detailed rock mass rating data at the investigated sites. In the following a brief account is given of the characteristics in each of these environments, which are so different that they likely need to be modelled separately. Further details may be found in [Hagelia, 2018a, b; Mannvit 2016].

### 3.1 *Freshwater environment*

The freshwater environment was characterised by surface carbonation due to atmospheric $CO_2$, reaching only about 20 mm depth when sprayed concrete was exposed to exhaust fumes. Carbonation in unexposed sprayed concrete behind inner linings was even

*Table 2: Deterioration mechanisms encountered in Norwegian sprayed concrete for rock support S = steel fiber, P = polypropylene fiber, C-S-H = calcium silicate hydrate (continued overleaf)*

| **Type of degradation** | **Potential effects on cement paste** | **Potential effects on fiber reinforcement** | **Exposure environment and agents** |
|---|---|---|---|
| Ordinary surface carbonation | Degradation of portlandite & C-S-H in surface region. Low permeability. pH ~ 8-9 | S: Corrosion as consequential damage<br>P: No effect | Atmospheric $CO_2$ Tunnel fumes. All environments |
| Internal carbonation<br>Popcorn calcite deposition (PCD). Related to decalcification. Trough solution process | Internal degradation of portlandite & C-S-H. Formation of calcite spots in Ca-poor silica gel. Loss of strength. Increased permeability pH ~ 8-9 | S: Corrosion as consequential damage<br>P: No effect | Dissolved $HCO_3^-$ in ground water penetrating into concrete in many environments. Depending on water pressure |
| Decalcification<br>Through solution process | Ca -leaching from portlandite & C-S-H.<br>Loss of strength<br>Increased permeability<br>pH ~ 8-12 | S: Corrosion as consequential damage<br>P: No effect | Dissolved carbonic acid or ordinary fresh ground water with $HCO_3^-$ penetrating into concrete. Depending on water pressure |
| Chloride penetration<br>Through solution process | Slight loss of strength.<br>pH ~ < 10 to > 13 | S: Corrosion as consequential damage<br>P: No effect | 1) Subsea environments. Depending on water pressure. Brackish to seawater-like ground waters<br>2) De-icing salts |

| Type of degradation | Potential effects on cement paste | Potential effects on fiber reinforcement | Exposure environ-ment and agents |
|---|---|---|---|
| *Thaumasite sulfate attack (TSA)* Through solution process, frequently related to decalcification and PCD | Degradation of portlandite & C-S-H. Loss of strength Increased permeability pH ~ 8-12. | S: Corrosion as consequential damage when PCD is present P: No effect | Dissolved sulfate and bicarbonate in ground water penetrating into concrete. Alum shale & subsea environ-ments. Depending on water pressure |
| *Acid attack* (commonly $H_2SO_4$) Trough solution process | Fast degradation of portlandite & C-S-H, significant strength reduction and much increased permeability pH < 2 to 5 | S: Corrosion as consequential damage P: Not studied. Likely some effects | Related to sulfide oxidation and dissolution of certain sulfates. Alum shale and sulfide bearing gneiss, notably after drawdown of ground water table |
| *Magnesium penetration.* Trough solution process | Mg replacement of Ca in C-S-H and formation of $Mg(OH)_2$ Loss of strength. Increased permeability pH ~10 | S: Corrosion as consequential damage P: No effect | Subsea tunnels notably at high water pressure in rock mass with high hydraulic conductivity |

| Type of degradation | Potential effects on cement paste | Potential effects on fiber reinforcement | Exposure environment and agents |
|---|---|---|---|
| *Biofilm with Mn & Fe bacteria* combined with ingress of aggressive ions from saline ground water<br>NB: Not all biofilms are harmful. | Degradation of portlandite & C-S-H, formation of Mn-Fe biominerals, ± TSA, PCD & Mg-attack. Loss of strength and outer mass loss. High permeability.<br>pH ~5.5-7.5 | S: Severe corrosion<br>P: Not documented in Norway (see Hughes, 2012, 2013) for effects of photosynthetic microbes and algae) | Some subsea environments.<br><br>Other environments yet to be investigated |
| *Mechanical loads* | Macro and micro cracking. Increased permeability beyond level expected by w/b-ratio of concrete mix | S: Corrosion as consequential damage<br>P: No effect under ordinary loads | Instable rock mass: mainly where designed rock reinforcement is insufficient |
| *Frost action*<br>Regarded as of minor importance [Davik, 1997,1998] | Macro and micro cracking, mainly observed in old obsolete sprayed concrete mixes | S: Corrosion as consequential damage<br>P: No effect | Freeze-thaw cycles. Frost Index |

shallower [Fjose, 2015, Hagelia, 2018a]. De-icing salts had occasionally penetrated to ca. 10 mm depths. Calcium leaching and outer calcite precipitation occurred at places, whilst Popcorn calcite deposition (PCD) within Zone A rarely occurred despite variable permeability of the adhesion zones. The w/b-ratios in the investigated concretes were 0.41 to 0.49. Due to the complexity of exposure conditions and design it was not possible to establish that carbonation was increasing over time. Sprayed concretes in freshwater environment were essentially sound up to 23 years of exposure [Hagelia, 2018a, b].

### 3.2 *Mildly acidic environment*

The mildly acidic environment characterised by pH = 5.5 – 6 and sulfate contents around 100 mg/L was investigated in a service tunnel without traffic. The object is located within

Eocambrian black shale. The w/b-ratio was about 0.50. Surface carbonation varied from 1 – 13 mm. Calcium leaching and surface precipitation of calcite and thenardite had occurred during the first 13 – 16 years, although the concrete was mainly sound in 60 – 110 mm thick sprays. Leaching with local full-scale thaumasite sulfate attack (TSA) was restricted to an extremely thin concrete layer about 20 mm thick [Hagelia et al., 2003, Hagelia 2018a,b]. The Eocambrian black shale environment in Norway is apparently less harmful to sprayed concrete than the Alum shale environment, but further investigations of road tunnels is required.

### *3.3 **Alum shale environment***

Alum shale is a potentially acid producing black shale of Cambrian-Ordovician age. The investigated sites were characterised by sulfate concentrations ranging mainly from 500 to 2000 mg/L and bicarbonate ranging from about 50 to 300 mg/L. pH measurements in ambient ground waters were around 7 [Hagelia et al., 2003, Hagelia, 2011]. Low pH environments, which are frequently associated with Alum shale [Bastiansen et al., 1957; Moum & Rosenqvist, 1959], were encountered on some adhesion zones in our investigated tunnels. In general, outer surface carbonation varied from 0 to 4.5 mm depths, whilst locations with de-icing salts were not available for testing [Hagelia, 2018a,b]. Calcium leaching and outer calcite precipitation is quite common. Two main degradation mechanisms occur: 1) Thaumasite sulfate attack (TSA) associated with calcium leaching and Popcorn calcite deposition (PCD) affected Zone A and to a certain extent Zone C, and 2) sulfuric acid attack on some adhesion zones. Such localised acid attack has caused progressive loss of adhesion, leading to spalling; cracking and localised acid attack across the entire sprayed concrete layer (Figure 4): Oxygen permeability of sprayed concrete was clearly sufficiently high to induce sulfide oxidation in the adjacent Alum shale. In addition, drawdown of the groundwater can lead to oxidation and acidification at even larger scale [Bastiansen et al., 1957]. Increasing w/b-ratios from 0.40 to 0.50 indicated an increase in degradation due to TSA and PCD in Zone A. As seen in Figure 4 the effects of sulfuric acids acting from permeable adhesion zones locally had a profound effect of degradation. However, due to the complex spatial variation of exposure conditions, it was not obvious that degradation by TSA, PCD and acid attack was increasing over time. The effect of designed spray thickness is more important: Sprays thicker than 100 mm with w/b-ratio = 0.40, high contents of silica fume, capillary porosity < 20% and good adhesion were mainly intact after 22 years [Hagelia, 2018a, b].

### 3.4 *Highly acidic environment*

Severe cases of acid rock drainage occur in certain regions of Norway. pH-values lower than 3 have been encountered. However, investigation into the durability of sprayed concrete for rock support has not yet been undertaken in this exposure environment.

### 3.5 *Subsea environment*

Surface carbonation in subsea tunnels reached 4 mm depths. Calcium leaching and outer calcite precipitation was quite common. The main degradation mechanisms operating in the subsea environment were two-fold: 1) abiotic attack due to saline ground water, acting mainly within Zone A, and 2) variable effects of Mn-Fe biofilms acting from the outer surface (Zone C). The abiotic attack involved penetration of chloride, magnesium, sulfate and bicarbonate, leading to calcium leaching, magnesium substitution of C-S-H, PCD and TSA. The biofilms showed complex behaviour, involving mild acidification with occasionally severe material loss within Zone C. Simultaneous action of abiotic attack from the adhesion zone and biofilm attack within the outer surface region was most detrimental, leading to thinning of the sprayed concrete. However, these circumstances do not always coincide [Hagelia, 2011, 2018a]. Layers thinner than 50-100 mm were most vulnerable. The degradations observed in the investigated tunnels varied from nearly absent to locally very significant, sometimes even after few years in service. The subsea environment was characterised by sulfate, Cl and Mg concentrations about 500-3300 mg/L, 5000 to 50.000 mg/L and 570 to 1420 mg/L, respectively. The pH was commonly varying between 7.5 to 8, whilst biofilms had pH ranging from about 5.5 to 6.5 [Hagelia, 2011]. Some biofilms did not develop low pH and are probably non-aggressive. It was difficult to establish a general effect of aging, due to the variable effects of w/b-ratios, water loads etc., whilst the thickness of the spray clearly influenced the durability. It was obvious that sprays thicker than 100 mm, with low w/b-ratios (< 0.41) and capillary porosities below 20% were mainly intact after 15 to 25 years, being comparable with results from the Alum shale environment. Also, good adhesion or adhesion zones filled with brucite and calcite promoted long term durability [Hagelia, 2018a, b]. The role of biofilms is currently under investigation by Sabina Karačić at Chalmers - Gothenburg, including identification of microbial communities by DNA techniques [Karačić, 2018].

### 3.6 *Steel fiber corrosion*

Steel fiber corrosion is a consequential damage of cement paste degradation. Corrosion of steel fibers in the alum shale environment was most destructive in presence of calcite. Fiber corrosion in subsea tunnels was locally severe in concretes thinner than about 50 mm, whilst mainly absent in sprays thicker than 100 mm as seen in Figure 5. The data are based on visual inspection of subsea concrete cores followed by systematic thin section work. The corrosion status in each zone (Zones A, B and C in Figure 1) was rated from 0 to 3. Zone B with intact paste was usually without steel fiber corrosion (rate = 0) and occasionally very minor marginal corrosion only traceable under the petrographic microscope (rate = 1). Zone A and Zone C with degraded pastes displayed variable fiber corrosion (rates = 0 to 3). Figure 5 *shows the effects of steel fiber corrosion in two different ways*: The y-axis represents a rating of the entire cross-section, where the influence of corrosion in each zone has been weighted. Marginally destructive corrosion (1-2) and severe to fully destructive corrosion for an entire core are indicated by the ranges 1-2 (orange) and 2-3, (red) respectively. Some sprays thinner than about 60 mm were characterised by severe to fully destructive fiber corrosion across the sprayed concrete layer (rate = 3), whilst there is a clear trend towards lesser influence of corrosion with an increasing thickness. Secondly, the individual coloured points show the worst case of corrosion in each core. Only red and orange symbols represent important fiber corrosion. The single red point with arrow is a very unusual case with biofilm attack from the adhesion zone. The most destructive fiber

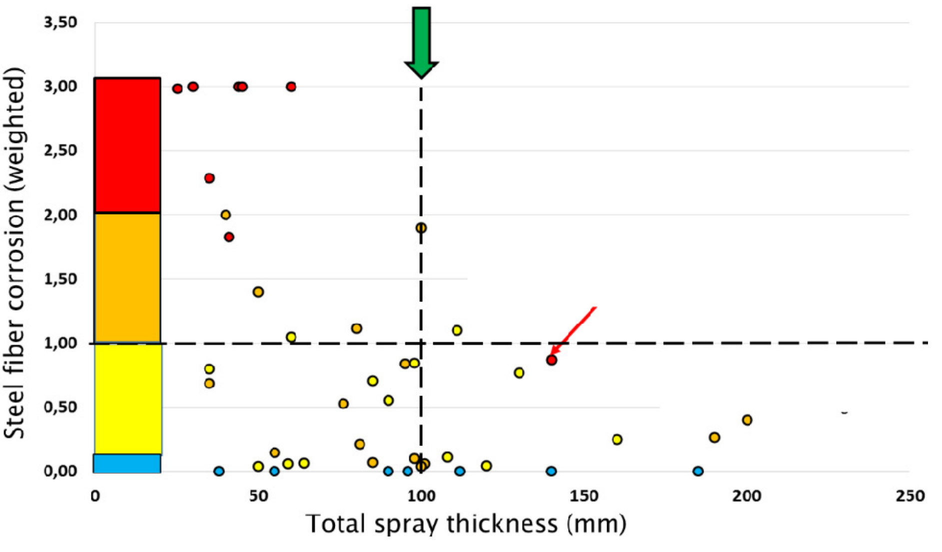


*Figure 5. Thickness versus steel fiber corrosion rated by weighting of influence across the thickness (see text for explanation). Each point is also coloured showing the worst case in each core. Red = severe to fully destructive (rating 3), orange = marginally destructive (rating 2) yellow = insignificant to marginal corrosion only visible in microscope (rating 1), blue = no corrosion (rating 0). Results from subsea tunnels*

corrosion occurred in outer zone C underneath acid producing biofilms, being associated with very extensive cement paste degradation. Despite elevated chloride contents (fast anodic process) in many sprays, the steel fibers were mainly intact [Holm, 2011a,b; Hagelia, 2018a,b; Mannvit, 2016], which can be explained by very sluggish oxygen penetration (slow cathodic process) [Hagelia, 2018a]. This seems related to the positive mechanical effects from fibers, which tend to prevent microcracking and inhibit steel fiber corrosion [Berrocal, 2017]. Microscopy of our subsea concretes showed few to occasionally abundant microcracks, which were mainly 10 - 20 µm wide. In contrast, crack widths about 100 µm cause fiber corrosion and loss of compressive and tensile strength [Nordström, 2016]. Hence, oxygen permeability is a clear issue for future modelling.

# 4 Discussion

*One may give a problem such a form that it is always possible to solve it,*
*something that can be done with any problem.*
*Instead of searching for a relationship without knowing if it exists,*
*one should ask if such a relationship really is possible.*
Niels Henrik Abel, 1828.

## *4.1 General*

In the present author's opinion, the modeller should always keep in mind the above quote from the mathematician Niels Henrik Abel. It is implicit that any computer model does represent a formulation and a formalisation of the problem, which inevitably will provide a "solution": *Numbers will always turn up!* However, the question is if the model basis is sound and rich enough in order to cope with the complexity of the real durability development of sprayed concrete. Application of "relationship" in Abel's statement in connection to modelling means "the relationship between durability development of sprayed concrete in tunnels and the durability results given by a computer model". The only way to understand if such a relationship really exists is through a thorough characterisation of tunnel concretes and their complex and highly variable contexts over long periods and compare this to the outcome of models whose input data must be obtained from well-characterised individual sites at different times.

Development of a comprehensive computer model for durability prediction of sprayed concrete is indeed wanted but difficult. It is necessary that the modellers have a good insight into the practical and theoretical sides of the problem, preferably by personal experience from tunnel surveys, sampling and laboratory investigations involving concrete petrography. In real life, the question of when to intervene and undertake repair is very important because it has an effect on society. Tunnel closure is costly, not just for the owners, but also because it influences traffic conditions, transport and environment. Due to the complexity of the sprayed concrete durability problem as described above, it is obvious that computer modelling must be developed step by step for each limited problem and then verified before further integration into a global model system. The following discussion gives a brief account of model approaches and is not exhaustive.

### *4.2 Sketches for model approaches*

The main durability challenges in Norwegian sprayed concrete occur in the Alum shale environment and the subsea environment. Similar challenges have been reported from many other countries and should be main targets for computer modelling. In view of Figure 3, several partial model problems can be envisaged. Regarding the structural integrity of sprayed concrete, the following themes are very important:

- The conditions affecting the adhesion zone, involving primary permeability and later effects by dissolution and precipitation
- The hydraulic conductivity and gas permeability of the sprayed concrete layer, e.g. the degree of resistance against degradations due to through solution processes

Accumulated evidence shows that high permeability of the adhesion zone facilitates a high degree of degradation in sprayed concrete adjacent to the rock mass (Zone A, Figure 1). Adhesion zones in the alum shale environment showed important signs of acidification due to sulfide oxidation in adjacent shale, hence causing significant weakening and spalling of rather thin (ca. 50 mm) sprayed concrete layers after some years. In such cases leaching by sulfuric acid made way for TSA and PCD within Zone A, where dissolved Ca, sulfate and carbonate ions reach higher pH-regions deeper inside the concrete slab. The possibility of a similar, albeit slower, development also in thicker sprays is uncertain. In contrast, permeable adhesion zones in the subsea environment were characterised by precipitation of brucite and calcite where saline ground waters had reacted with the alkaline fluids from concrete. Precipitation leads to blocking of water channels and reduced influence of aggressive ions in the long run: The durability development in subsea sprayed concrete partly depends on the degree of fill by brucite and calcite. Model approaches involving dissolution and precipitation in response to different ground water compositions and concrete materials are possible to design, as based on hydrogeochemical computer codes such as PHREEQC [Appelo & Postma , 2005].

Modelling of oxygen transport through sprayed concrete is an important task, with respect to steel fiber corrosion in chloride-laden concrete, as well as the potential for sulfide oxidation in the alum shale substrate. Accumulated empirical evidence has shown that a relatively thick sprayed concrete layer contributes to slow down these deteriorations. Likely model calculations may assist in better establishing critical thicknesses with respect to steel fiber corrosion and sulfide oxidation in the alum shale substrate for different concrete materials.

When taking into account the hydraulic conductivity and gas permeability of different concrete mixes it will further be possible to estimate degradation rates for specified deterioration mechanisms across sprayed concrete layers. Ingress of aggressive ions such as chloride, sulfate and magnesium can have a significant impact on durability, but these ions have different chemical properties. If realistic computer models can be established, future developments towards the design lifetime of 100 years may be better estimated. This, among others, requires implementation of the chemical properties of cement hydrates, the influence of aggressive waters on the concrete fluid composition, and that resulting degradation products compare well with observed reactions products in tunnels. It is important to keep in mind that several degradation mechanisms usually take place at the same site, with somewhat different mechanisms acting within the different zones (cf. Figure 1). The impact of each single mechanism may also vary over time. In this respect, the role of biofilms can be especially difficult to predict. This is due to important changes within biofilm communities over time, which have an impact on the aggressiveness of associated waters [Hagelia, 2011, 2013, Karačić, 2018].

Modelling the effects of hydrogeological variables is an important task, because they govern the access of aggressive waters. Computer modelling of different hydrogeological scenarios and their impact on different sprayed concrete mixes and design thicknesses should be attempted. Empirical evidence show that water pressure has an important influence on degradation rates. A problem, which is implicit in hydrogeological modelling, is that severe concrete degradations mostly are scattered local scale phenomena. Water flow is in most cases governed by the flow laws for discrete cracks, hence depending on their local apertures, roughnesses and tortuosities, which are difficult to characterise in tunnels. Simple Darcy conditions cannot generally be assumed.

All model results must be verified through relevant laboratory experiments, which should be designed in accordance with empirical evidence gathered from real tunnel concrete. In all circumstances, model results should just be regarded as part of the basis for further judgements. Decisions on when to close a tunnel and how to undertake repairs depends on many other equally important factors, involving evaluation of model output versus real on-site conditions, budgeting, technical issues as well as effects of the tunnel closure on the entire transport system.

# 5 Conclusions

The main durability challenges in sprayed concrete reinforced rock tunnels in Norway were found in the Alum shale and subsea environments, which should be a main target for computer modelling. However, the complex interaction of all variables described above seems very difficult to handle, leaving modelling with boundary conditions so wide that the practical application might seriously be questioned. Even if such models can be established there is still a need for modelling the effect of variably degraded sprayed concretes on tunnel stability as a whole. However, it would be fruitful to undertake computer modelling of specific problems such as oxygen permeability of sprayed concrete and its influence on steel fiber corrosion or sulfide oxidation. Such models may have practical application provided they are formulated on the basis of real tunnel contexts and input data therefrom. Until further progress has been made, the responsible tunnels owner will inevitably have to rely on monitoring as basis for durability prediction. This seems to be the only way to prescribe realistic solutions, hence avoiding erroneous decisions and wrong messages to the budgeting body of our organisations.

***Acknowledgements***
The author wishes to thank good colleagues at NPRA, Norconsult and Mannvit for support, and most notably Reidar Kompen (NPRA) for sharing his extensive practical and theoretical experience over two decades. Assistance and discussions with Jan Viggo Holm (†) of Norconsult and Gísli Guðmundsson of Mannvit are gratefully acknowledged. The author is also much indebted to Klaas van Breugel and Oğuzhan Çopuroğlu for inviting me as a PhD candidate at TU-Delft in 2010 and to Guang Ye, TU-Delft, for encouraging me

to modify the first version of this paper and elaborate further on ideas for a future modelling approach. Comments of an anonymous reviewer helped improving the paper.

## Literature

Appelo, C.A.J., Postma, D. (2005). *Geochemistry, ground water and pollution* (2nd Ed). A.A. Balkema Publishers, Leiden, 649 pp.

Barton, N., Grimstad, E. (2004). The Q-system following thirty years of development and application in tunnelling projects. Rock Engineering – Theory and Practice, Proceedings of ISRM Regional Symposium EUROCK 2004, Salzburg, Austria, p 15-18.

Bastiansen, R., Moum, J., Rosenqvist, I.Th. (1957). Contribution to highlight certain construction problem related to Alum Shale in Oslo. Publication No. 22, Norwegian Geotechnical Institute, 69 pp (In Norwegian with English summary).

Berrocal, C.G. (2017). *Corrosion of steel bars in fiber reinforced concrete: Corrosion mechanisms and structural performance*. PhD-thesis, Chalmers University of Technology, Gothenburg, Sweden, 69 pp with Appendices.

Bjøntegaard, Ø., Myren, S.A., Beck, T. (2018). Quality control of fiber reinforced sprayed concrete: Norwegian requirements and experienced from laboratory studies and tunnel projects. In: S. Engen, T. Bech, S. Myren (Eds.), 8th International Symposium on Sprayed Concrete – Modern Use of Wet Mix Sprayed Concrete for Underground Support. Trondheim, Norway: pp 97-107.

Breugel, K. van (2017). Urgency and challenges of ageing in science and engineering. In: K. van Breugel, D. Koleva, T. van Beek (eds): *The ageing of Materials and Structures: Towards Scientific Solutions for the Aging of our Assets*: p. 3-13.

Breugel, K. van, Polder, R.B., Rooij, R. de, 2008, Validation of models for service life prediction of marine structures, Structural Faults and Repair, June 10-12, Edinburgh

Davik, K.I. (1997). Proper use of sprayed concrete in tunnels. Parts A, B, C, D, E and Final Report Norwegian Public Roads Administration (in Norwegian).

Davik, K.I. (1998). Proper use of sprayed concrete in tunnels. *Nordic Road and Transport Research* 1: 16-17.

Fjose, A. (2015). Deterioration of sprayed concrete at E39 Hopstunnelen and Nesttuntunnelen. MSc-thesis, Norwegian University of Science and Technology, Trondheim, Norway, 244 pp (in Norwegian).

Franzén, T., Garshol, K.F., Tomisawa, N. (2001). ITA/AITES Accredited Material, Sprayed concrete for final linings: ITA working group report. *Tunnelling and Underground Space Technology*, 16: 295-309.

Gulland, J. (2015). Sprayed concrete tested by destructive and non-destructive methods. MSc-thesis, Norwegian University of Science and Technology, Trondheim, Norway, 138 pp (in Norwegian).

Hagelia, P., Sibbick, R.G., Crammond, N.J., Larsen, C.K. (2003). Thaumasite and secondary calcite in some Norwegian concretes. *Cement and Concrete Composites*, 2003. 25: 1131-1140.

Hagelia, P. (2008). Does the EN 206-1 Exposure classification apply to tunnel concrete? Nordic Exposure Sites – Input to revision of EN 206. Workshop Proceedings from a Nordic Miniseminar, Hirtshals, Denmark: pp 241-263.

Hagelia, P. (2011). *Deterioration mechanisms and durability of sprayed concrete for rock support in tunnels*. PhD-thesis, Delft University of Technology, the Netherlands. 205 pp with Appendices.

Hagelia, P. (2013). Interaction of abiotic and biochemical reactions and their role in concrete deterioration. *Concrete*, Vol 47 No 6: 49-51.

Hagelia, P. (2018a). Summary of durability developments of sprayed concrete used for rock support in different tunnel environments. R & D Program Durable Structures. Report no. 566, Statens vegvesen (in Norwegian): 388 pp

Hagelia, P. (2018b). Durability of sprayed concrete for rock support – A tale from the tunnels. In: S. Engen, T. Bech, S. Myren (Eds.), 8th International Symposium on Sprayed Concrete – Modern Use of Wet Mix Sprayed Concrete for Underground Support. Trondheim, Norway: pp 172-187

Holm, J.V. (2011a). Modern road tunnels – Sprayed concrete in the Freifjord tunnel. Sprayed concrete. Norconsult, report to project, No 5013053 (in Norwegian).

Holm, J.V. (2011b). Modern road tunnels – Sprayed concrete in the Oslofjord tunnel. Norconsult, reports to project No 5013053 (in Norwegian).

Hoseini, M., Bindiganavile, V., Banthia, N. (2009). The effects of mechanical stress on permeability of concrete: A review. *Cement and Concrete Composites*, 31: 213-220.

Hughes, P. (2012). A new mechanism for accelerated degradation of synthetic fibre reinforced marine concrete. *Concrete*, Vol. 46, No.9: 18-20.

Hughes, P., Fairhurst, D., Sherrington, I., Renevier, N., Morton, L.H.G., Robery, P.C., Cunningham, L. (2013). Microscopic examination of a new mechanism for accelerated degradation of synthetic fibre reinforced marine concrete. *Construction and Building Materials*, 41: 498-504.

Karačić, S. (2018). *Microbially induced concrete degradation in subsea tunnels. Community structure of biofilms from sprayed reinforced concrete in the Oslofjord tunnel*. Licentiate thesis. Chalmers University of Technology, Gothenburg, Sweden, 36 pp with Appendices.

Lagerblad, B., Fjällberg, L., Vogt, C. (2010). Shrinkage and durability of shotcrete. In: E.S. Bernard (ed): *Shotcrete: Elements of a System*. Taylor & Francis Group, London, 173-180.

Li, K. (2016). *Durability design of concrete structures. Phenomena, modelling and practice*. John Wiley & Sons Singapore Pte. Ltd.

Mannvit (2016). Durability investigation of sprayed concrete in seven tunnels. R & D Program Durable Structures 2012-2015. Report no. 475, Statens vegvesen (in Norwegian).

Moum, J., Rosenqvist, I.Th. (1959). Sulphate attack on concrete in the Oslo Region. *Journal of the American Concrete Institute*, Proceedings Vol 56, Title 56-18: 8 pp.

Nordström, E. (2016). Evaluation after 17 years' field exposure of cracked steel fiber reinforced concrete. BeFo Report 152, Stockholm, Sweden, (in Swedish with English summary).

Schlangen, E., Garboczi, E.J. (1997). Fracture simulation of concrete using lattice models: Computational aspects. *Engineering Fracture Mechanics*. 2/3: 319-332.

Wegen, G. van der, Polder, R.B., Breugel, K. van, 2012, Guideline for Service Life Design of Structural Concrete – a performance-based approach with regard to chloride induced Corrosion, *HERON*, 57 (3), 153-168