# INVESTIGATION OF THE EFFECTS OF LEACHING ON THE SCALING RESISTANCE OF CONCRETE

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## ABSTRACT

Damage to the concrete surface can be observed at the waterline of hydraulic structures in fresh water bodies in cold climates. Gradual deterioration of the concrete surface leads to exposure of coarse aggregate. Superficial damage at the waterline is commonly assumed to be caused by drifting ice floes. However, deterioration of concrete at the waterline may also involve leaching and frost action. The objective of this study is to investigate if leaching of calcium compounds changes the surface properties of concrete in such an extent that the scaling resistance is reduced.

Specimens with water to cement ratio 0.62 and 0.54 were submerged in deionised water at +20°C and pH 4 ± 0.1 in order to accelerate leaching of calcium compounds. The scaling resistance of concrete was assessed according to the Swedish test method SS 13 72 44. The results show that the scaling resistance of concrete is reduced if calcium compounds have been leached out from the surface. The results also show that the longer the time of leaching, the greater the reduction in scaling resistance. Superficial damage at the waterline of hydraulic structures in fresh water bodies in cold climates is most likely caused by interaction between leaching, frost action and abrasion.

**Keywords:** Concrete, Leaching, Scaling resistance, Freeze-thaw cycles, Hydraulic structures.

## 1 INTRODUCTION

Damage to the concrete surface can be observed at the waterline of hydraulic structures in fresh water bodies in cold climates. Hydro power structures in Sweden are an example of such structures. Gradual deterioration of the concrete surface results in exposure of coarse aggregate, see Figure 1. The greatest amount of damage is found at the waterline, which normally corresponds to the maximum water level. The amount of damage decreases with increasing water depth. In a long-term perspective, also the reinforcing steel can be exposed. Hence, the structural integrity and durability of these structures can be reduced.

Superficial damage at the waterline is commonly assumed to be caused by drifting ice floes. Abrasive wear of the concrete surface may occur if ice floes push against the structures. This scenario is true regarding concrete structures at intakes and spillways on the upstream side of hydro power plants where the river current leads ice floes towards the structures. On the downstream side, however, the water flows away from the structures and carries away the ice floes. In spite of this fact, superficial damage at the waterline can be observed on the downstream side of hydro power plants. Such observations indicate that damage to the concrete surface is not exclusively caused by ice abrasion.

The deterioration process of the concrete surface at the waterline may involve carbonation, dissolution and leaching of calcium compounds, frost action and ice abrasion. Even though the resistance of concrete to a certain deterioration mechanism is good, the effects of other mechanisms may significantly reduce the resistance to the first mechanism. Since hydraulic structures often are subjected to a number of deterioration mechanisms, synergy may occur. Synergy is defined as the interaction of two or more elements, which together produce an effect greater than the sum of their individual effects.

The objective of this paper is to investigate if leaching of primarily calcium compounds from the concrete surface reduces the scaling resistance of concrete. If this is the case, it may explain why superficial damage can be seen at the waterline of hydraulic structures in fresh water bodies in cold climates. This paper includes results on the scaling resistance of concrete from both existing structures and concrete specimens subjected to leaching in the laboratory.


*Figure 1: Coarse aggregate exposed at the waterline on the upstream face of a concrete dam. The water level was about 0.3 m lower than normal when the picture was taken.*

## 2 DETERIORATION OF CONCRETE

### 2.1 Exposure conditions

The climate in Sweden is variable, especially in the northern parts of the country where summers are warm and winters are cold. Air temperatures down to -30°C are common during the winter months. The difference between daily minimum temperatures in winter and daily maximum temperatures in summer is usually in the range of 50 to 60°C. During the spring and autumn months, the air temperature frequently crosses the freezing point of water.

In Figure 2, the same structure is shown in the morning and in the afternoon on the same day. Ice has formed at the waterline during the night, while it has melted away during the day. The next morning, the concrete surface was covered with ice again. Krus (1996) theoretically showed that concrete structures can be subjected to up to 50 freeze-thaw cycles over a year in northern Sweden. In mid winter, however, a band of ice frozen solid to the concrete surface can be seen for months at the waterline of hydraulic structures.

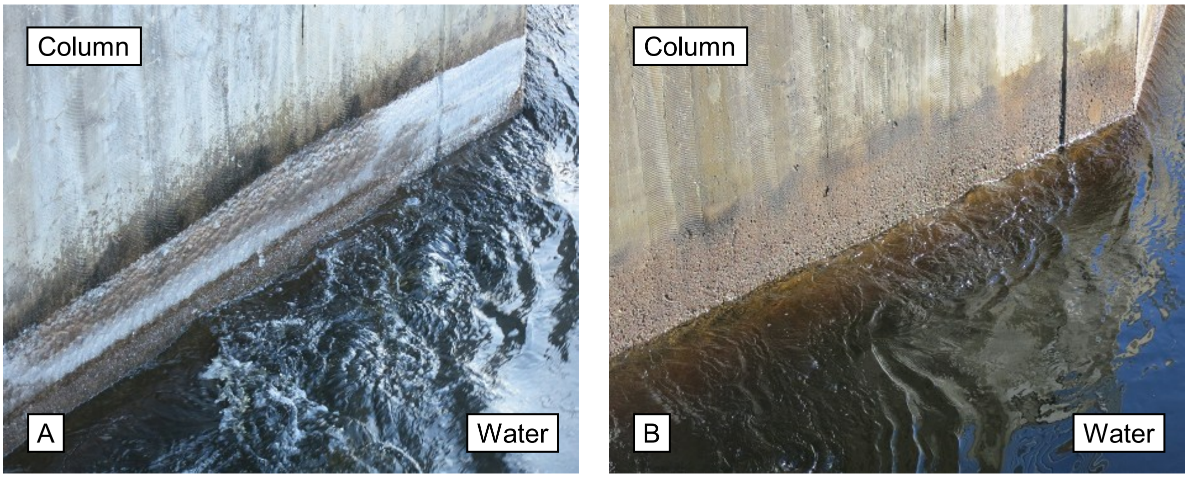


*Figure 2: The concrete surface at the waterline is covered with ice in the morning [A], while the ice has melted away in the afternoon [B].*

Concrete structures partly submerged in water are affected in different ways due to varying water chemistry of the water bodies. The river water in Sweden may be considered aggressive with regard to the risk of leaching of calcium compounds from the concrete surface. Drugge (2001) showed that the calcium ion concentration of the water in Swedish rivers, due to the geology of Sweden, is low in comparison with most other rivers around the world. For example, the calcium ion concentration is about 3 mg/l in the river Lule älv in northern Sweden. Low content of calcium ions in the river water increases the capacity of the water to dissolve calcium compounds from the concrete surface.

## 2.2 Frost resistance of concrete

The design life of hydraulic structures has traditionally ranged from 50 to 100 years. In cold climates, the frost resistance of concrete is of great importance to the durability of the structures. Powers (1945) stated that concrete subjected to frost action can be damaged either by scaling or internal damage. Scaling deteriorates the surface, whereas internal damage lowers the compressive and tensile strength of concrete. Powers proposed the hydraulic pressure theory to explain frost damage. The theory was based on the fact that the volume of water expands by about 9% upon freezing. When excess water is forced out of the capillary pores, a hydraulic pressure gradient is created by the flow resistance in the cement paste. Frost damage occurs if the hydraulic pressure exceeds the tensile strength of cement paste.

Later findings by Powers and Brownyard (1948) showed that the freezing point of water in cement paste is dependent on the pore size. Nucleation of ice crystals becomes more difficult as the pore size decreases. When water freezes in large capillary pores, water in small capillary pores and gel pores remains unfrozen. The amount of freezable water increases with decreasing temperatures. Based on these findings, Powers and Helmuth (1953) proposed the microscopic ice lens growth theory. Ice crystals in large capillary pores attract water from the gel and smaller capillary pores. Consequently, water moves into the large capillary pores and causes the ice crystals to grow to microscopic ice lenses.

The frost resistance of concrete is normally improved when an air entraining agent is added to the concrete mix. Artificially created air voids are not filled with water by capillary forces and therefore remain air filled. Hence, Powers (1949) explained that air voids provide empty spaces within the concrete where ice can form without exerting pressure on the pore walls.

### 2.3 Leaching of calcium compounds

All hydration products of Portland cement are soluble in water to varying degrees. The rate at which calcium compounds are dissolved in water depends on the aggressiveness of water and the permeability of concrete. The process of dissolving calcium compounds in water is called leaching. Dissolution of the cement paste increases the pore volume and thus porosity. The most soluble hydration product is calcium hydroxide (CH), also known as portlandite. Calcium compounds are also dissolved from other hydration products, such as the CSH gel.

According to Beddoe and Dorner (2005), dissolution and leaching of calcium ions from the CH start when the pH value of the pore solution is below 12.6. Regarding the CSH gel, the corresponding value is 10.5. At pH values between 4.0 and 6.5, only a small amount of calcium remains in hydration products containing iron and aluminium. Calcium ions from the other hydration products are dissolved to a much lesser extent as long as there is CH left. At pH values below 2, the cement paste has been reduced to a silica gel residue.

Ekström (2003) investigated the effects of percolating water on the leaching process of concrete in hydro power dams. Besides the effects of percolating water, he also measured the remaining content of calcium ions in concrete specimens submerged in deionised water for two years. The results showed that leaching of calcium compounds was greater close to the surface than deeper into the specimens. In order to verify results from specimens produced and tested in the laboratory, it is also important to test specimens from existing structures.

## 3 STENKULLAFORS POWER PLANT

Stenkullafors power plant is situated along the river Ångermanälven in northern Sweden. Construction work began in the early 1980s and the power plant was commissioned in 1983. Slag cement called Massivcement was used in the concrete. The slag content of the cement was 65%. At the time of construction, concrete with cement content 300-350 kg/m$^3$ and water to cement ratio (w/c-ratio) between 0.50 and 0.55 was normally used in hydro power structures. In order to improve the frost resistance of concrete, an air entrainment agent was added to the concrete mix. Between 2004 and 2006, after more than 20 years, the spillway section of the power plant was rebuilt and the spillway crest was lowered by 4 m.

Hassanzadeh (2010) studied the scaling resistance of left over concrete from the spillway section. The scaling resistance was assessed according to the Swedish test method SS 13 72 44, which was originally developed to evaluate salt scaling resistance of concrete, see Svensk Standard (2005). The results showed that the scaling resistance of the outer surface was remarkably reduced compared to the cut surface. Some of the results from the study are presented in Table 3. The reduction in scaling resistance of the outer surface could, however, not be fully explained. Bleeding, carbonation and/or leaching of calcium compounds from the concrete surface were suggested as possible causes. Especially the uncertainty about the effects of leaching on the scaling resistance of concrete showed the need for further studies.

## 4 MATERIALS

In order to investigate the effects of leaching of primarily calcium compounds from the concrete surface, two concrete mixes were cast; w/c-ratio 0.62 and 0.54. The mix proportions, shown in Table 1, were selected to represent concrete mixes used during the most intense period of the Swedish hydro power development. The mix with w/c-ratio 0.62 is typical for concrete used in hydro power structures built between 1930 and 1950, whereas the mix with w/c-ratio 0.54 is typical for concrete used between 1950 and 1970. The w/c-ratio of concrete mixes used after 1970 is somewhat lower due to the use of more efficient admixtures.

A CEM I Portland cement (Anläggningscement) was used in the concrete mixes. It is a moderate heat and low alkaline binder developed in the 1980s. The clinker phase composition of the Anläggningscement is relatively similar to the Limhamn cements, which were often used in the construction of Swedish hydro power structures between 1935 and 1980.

Table 1. Proportions of the two concrete mixes with w/c-ratio 0.62 and 0.54

| **w/c-ratio** | **Cement** ($kg/m^3$) | **0-1 mm** ($kg/m^3$) | **0-8 mm** ($kg/m^3$) | **1-4 mm** ($kg/m^3$) | **4-8 mm** ($kg/m^3$) | **8-16 mm** ($kg/m^3$) |
|---|---|---|---|---|---|---|
| 0.62 | 325 | 335 | 440 | 65 | 110 | 835 |
| 0.54 | 300 | 320 | 300 | 75 | 200 | 950 |

After pre-mixing of cement and aggregate, water was added and mixed for three minutes. Next, concrete was cast into moulds of size 150x150x150 mm. The top surface of the moulds was covered with plastic foil until demoulding 24 hours later. The concrete cubes were then stored in lime saturated water at 20°C until the test of the 28-day compressive strength. Properties of the fresh and hardened concrete mixes are presented in Table 2. At the age of 28 days, the cubes intended for use were split into specimens of size 150x150x50 mm. A water sealant was applied to all surfaces except the test surface, see Figure 4.

Table 2. Properties of the fresh and hardened concrete mixes

| **w/c-ratio** | **Air Content** (%) | **Slump** (mm) | **Density** ($kg/m^3$) | **Strength 28 Days** (MPa) |
|---|---|---|---|---|
| 0.62 | 1.3 | 80 | 2375 | 40.2 |
| 0.54 | 4.1 | 25 | 2350 | 43.0 |

## 5 METHODS

Sets of three specimens were subjected to leaching and/or freeze-thaw cycles in order to study the effects of leaching on the scaling resistance of concrete. Dissolution and leaching of calcium compounds were accelerated when the specimens with w/c-ratio 0.62 and 0.54 were submerged in deionised water at +20°C and pH 4 ± 0.1. The pH-value was maintained by automatic addition of 1 mol/l nitric acid ($HNO_3$). The solution was renewed once a week. The test setup is shown in Figure 3 and it was based on work by Rozière et al (2009).

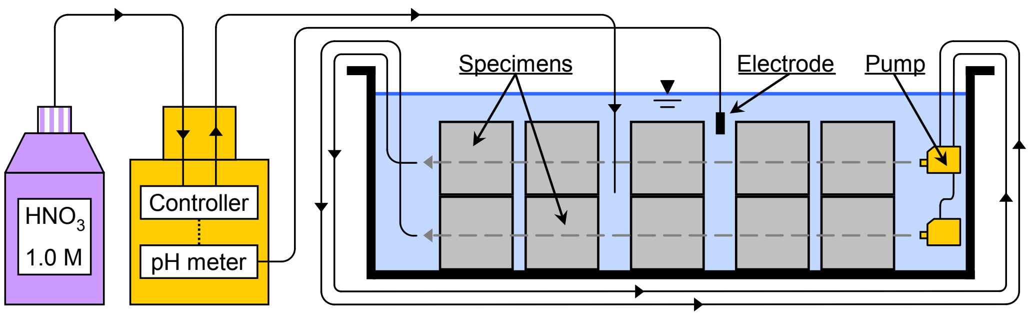


*Figure 3: Test setup used to accelerate leaching of calcium compounds from the surface of the concrete specimens. Nitric acid was automatically added in order to keep the pH value at 4.*

The scaling resistance of concrete was assessed according to the test method SS 13 72 44, see Svensk Standard (2005). The specimens were insulated on all sides except the test surface, which was covered with deionised water throughout the frost test. The freeze-thaw cycle was 24 hours long and during this period of time, the concrete surface temperature alternated between -20°C and +20°C. A full frost test procedure consists of 56 freeze-thaw cycles. The freeze-thaw cycle and the cross section of an insulated specimen are shown in Figure 4.

Reference specimens were subjected to the full frost test, whereas the specimens subjected to leaching prior to the frost test were subjected to only seven freeze-thaw cycles. The first set of specimens was submerged for one week prior to the frost test, whereas the second set of specimens was submerged for eight weeks. The effects of the frost test were quantified as the weight of loose materials collected from the concrete surface of each specimen. The weight of the loose materials was recalculated to weight loss per square meter ($kg/m^2$).

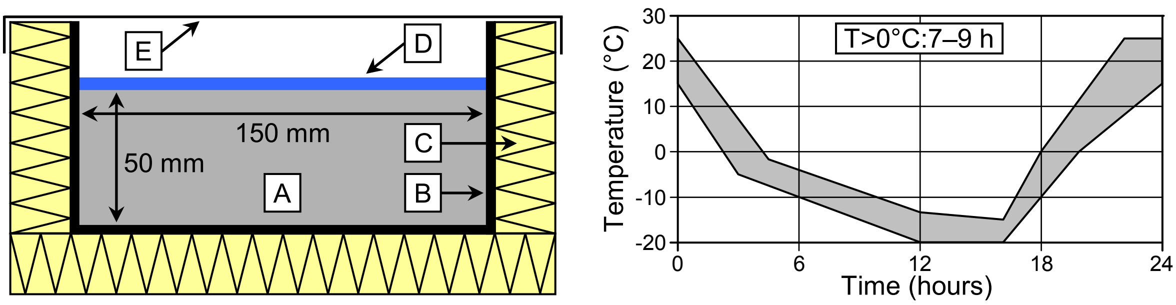


*Figure 4: Concrete specimen [A], water sealant [B], insulation [C], deionised water [D] and plastic foil [E]. The freeze-thaw cycle is shown in the picture to the right.*

## 6 RESULTS

When the scaling resistance of concrete from the spillway section of Stenkullafors power plant was assessed by Hassanzadeh (2010), it was shown that the scaling resistance of the outer surface was remarkably reduced compared to the cut surface. The scaling resistance of the cut surface was classified as *Very good* (< 0.1 $kg/m^2$), whereas the outer surface was classified as *Unacceptable* (> 1.0 $kg/m^2$). The results are presented in Table 3.

After 56 freeze-thaw cycles, no loose materials had been collected from the surface of the reference specimens with w/c-ratio 0.54. For the reference specimens with w/c-ratio 0.62, only a small amount of loose materials was collected throughout the frost test. When the specimens were submerged in deionised water at pH 4 for one respectively eight weeks prior to the frost test, the amount of loose materials collected from the surface increased somewhat.

The smallest amount of loose materials was collected from the specimens with w/c-ratio 0.54, which were subjected to leaching for one week prior to the seven freeze-thaw cycles. The greatest amount of loose materials was collected from the specimens with w/c-ratio 0.62, which were subjected to leaching for eight weeks prior to the seven freeze-thaw cycles.

Table 3. Accumulated weight of loose materials collected from the surface of specimens from Stenkullafors power plant (SPP) and from specimens with w/c-ratio 0.62 and 0.54

| **Specimen** | **Leaching** | **Surface scaling** (kg/m$^2$) | | | | |
|---|---|---|---|---|---|---|
| | | 7 days | 14 days | 28 days | 42 days | 56 days |
| SPP outer surface | 20+ years | 0.07 | 0.59 | 1.37 | 1.55 | 1.64 |
| SPP cut surface | - | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 |
| 0.54 cut surface | - | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.54 cut surface | 1 week | 0.01 | | | | |
| 0.54 cut surface | 8 weeks | 0.04 | | | | |
| 0.62 cut surface | - | 0.00 | 0.00 | 0.01 | 0.02 | 0.02 |
| 0.62 cut surface | 1 week | 0.02 | | | | |
| 0.62 cut surface | 8 weeks | 0.06 | | | | |

## 7 DISCUSSION

The results show that the scaling resistance of concrete is reduced if calcium compounds are leached out from the surface. Therefore, it is reasonable to assume that leaching increases the porosity and thus the average pore size in the surface layer. Hence, the risk of frost damage increases. The scaling resistance of the concrete mixes used in this study was reduced when the specimens were subjected to leaching for one week prior to the frost test. It was also shown that the longer the time of leaching, the greater the reduction in scaling resistance.

Regarding the specimens taken from the left over concrete from Stenkullafors power plant, the scaling resistance was remarkably reduced for the outer surface compared to the cut surface. In comparison with the specimens with w/c-ratio 0.62 and 0.54, the outer surface has been exposed to river water for more than 20 years. Even if the river water is less aggressive than deionised water at pH 4, the duration of exposure has increased the frost susceptibility of the surface layer. However, it has to be kept in mind that the type of cement is different and bleeding as well as carbonation may have affected the scaling resistance. Nevertheless, leaching of calcium compounds from the concrete surface has taken place over the years.

The concrete from Stenkullafors power plant and the concrete cast in the laboratory have in common that the scaling resistance is reduced when calcium compounds are leached out from the surface. Damage to the concrete surface at the waterline of hydraulic structures in cold climates, see Figure 1, is most likely caused by interaction between leaching and frost action. These deterioration processes together produce an amount of damage greater than the sum of their individual effects. In reality, also abrasive wear occurs if ice floes push against the structures. The damaged surface layer is thus removed and a new surface is exposed.

A possible deterioration process of concrete at the waterline of hydraulic structures in cold climates is that leaching of calcium compounds from the surface starts during the snowmelt runoff period. Hence, the concrete surface becomes frost susceptible and during the following winter, the surface layer is damaged by frost action and eventually removed by ice abrasion.

## 8 CONCLUSIONS

Based on the results presented in this paper, the scaling resistance of concrete is reduced if calcium compounds are leached out from the concrete surface. Hence, damage to the concrete surface at the waterline of hydraulic structures in fresh water bodies in cold climates is most likely caused by interaction between leaching, frost action and abrasion.

## ACKNOWLEDGEMENTS

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