



Effects of interactions between leaching, frost action and abrasion on the surface deterioration of concrete



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HIGHLIGHTS

- Interactions between leaching, frost action and abrasion cause surface deterioration.
- Both air-entrained and non-air-entrained concrete are susceptible to deterioration.
- Leaching significantly amplifies the effect of frost action on surface deterioration.
- Interactions between multiple degradation mechanisms accelerate deterioration.

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ABSTRACT

Surface deterioration of concrete occurs at the waterline of many hydraulic structures in contact with soft water in cold regions. Progressive disintegration of the surface leads to exposure of the coarse aggregate and ultimately of the reinforcing steel. Mechanical, physical and chemical processes could cause deterioration of concrete at the waterline.

The objective of this study was to investigate experimentally the effects of interactions between leaching, frost action and abrasion on the surface deterioration at the waterline of hydro power structures. The test methods were designed to represent the environmental conditions at the existing Swedish hydro power structures as accurately as possible. Air-entrained concrete with a water-to-cement ratio (w/c) of 0.54 and non-air-entrained concrete with a w/c ratio of 0.62 were used in the experiments.

It was demonstrated that the amount of damage caused by interactions between the three degradation mechanisms exceeded the total amount of damage caused by the mechanisms separately. Moreover, leaching significantly amplified the effects of frost action and abrasion for both concrete mixes. Considering the exposure conditions at Swedish hydro power plants, it was concluded that leaching combined with frost action accounts for most of the superficial damage observed at the waterline of these structures.

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1. Introduction

Surface deterioration of concrete occurs at the waterline of many hydraulic structures in contact with soft water in cold regions; see Fig. 1. Swedish hydro power plants are an example of such structures. The greatest amount of damage is found at the maximum water level, which generally corresponds to the normal water level. Progressive disintegration of the concrete surface leads to exposure of coarse aggregate. From a long-term perspective, the reinforcing steel can also become exposed and ultimately subjected to corrosion.

Superficial damage at the waterline is often assumed to be caused by drifting ice. Abrasive wear occurs if the mechanical loads exceed the strength of the concrete [1]. This scenario is most likely true for concrete structures in marine environments and at intakes and spillways on the upstream side of hydro power plants, where the river current leads ice floes towards the structures. However, on the downstream side of hydro power plants, water flows away from the structures and carries the ice floes away. Still, similar damage occurs at the waterline on the downstream side. Such observations indicate that surface deterioration at the waterline is not exclusively caused by ice abrasion.

Most hydraulic structures have components that are constantly submerged or partially submerged in water. The varying water chemistry of different fresh water bodies affects the concrete surface in various ways. For example, water can be more or less

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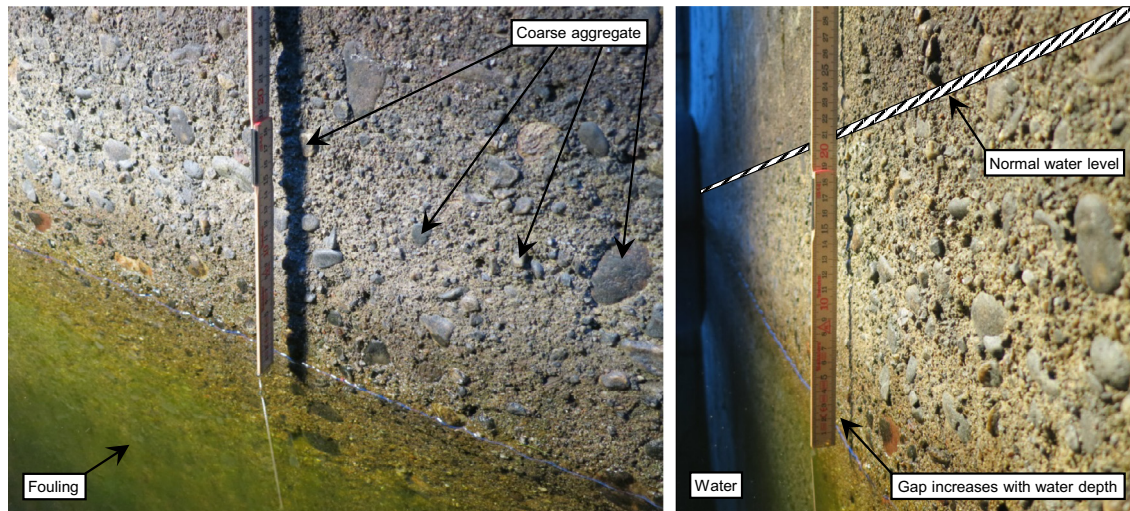


Fig. 1. Coarse aggregate exposed at the waterline of a concrete dam. The water level was decreased by approximately 0.2 m when the pictures were taken. Exposed aggregates were neither visible above the splash zone nor significantly below the temporary water level.

aggressive in its ability to dissolve components of the cement, i.e., leaching. The leaching kinetics is generally slow, but the impact can be substantial from a long-term perspective. In addition to leaching and ice abrasion, hydraulic structures situated in cold regions are exposed to frost action in winter.

The ability of concrete to resist single degradation mechanisms is normally assessed in standardised laboratory tests. Because many hydraulic structures are subjected to a number of degradation mechanisms, it is important to also consider the interactions between multiple mechanisms when assessing the durability of concrete.

The objective of this study is to experimentally examine the effects of interactions between leaching, frost action and abrasion on the surface deterioration of concrete in contact with soft water. The tests are designed to represent the exposure conditions at the waterline of existing Swedish hydro power structures as accurately as possible. However, the results should also be of interest in other countries with similar conditions. A literature review on leaching and freeze-thaw cycling is included in this paper to enhance understanding of how the mechanisms could interact.

2. Concrete durability

Durability is defined as the ability of concrete to resist weathering action, chemical attack and abrasion. Even if resistance to a certain degradation mechanism is satisfactory, the effects of additional mechanisms could significantly reduce the resistance to the first mechanism. Consequently, synergy can occur if multiple degradation mechanisms interact. Synergy is defined as the interaction of two or more mechanisms that together produce an effect greater than the sum of their individual effects.

The following sections describe the environmental conditions at hydraulic structures in cold regions. Additionally, the effects of leaching and freeze-thaw cycling on concrete durability are briefly reviewed for readers not familiar with the theory.

2.1. Environmental conditions in cold regions

In northern-situated countries such as Sweden, the climate varies greatly throughout the year. The difference between the daily minimum temperatures in winter and daily maximum temperatures in summer is usually in the range of 50 to 60 °C. Air temperatures as low as −30 °C are common during winter months. In the

spring and autumn periods, the air temperature frequently crosses the freezing point of water.

Rosenqvist et al. [2] showed that a band of ice frozen solid to the concrete surface is commonly present in mid-winter at the waterline of hydraulic structures. This formation of ice indicates freezing temperatures in concrete below the water level. Hence, it is important that the concrete used in hydraulic structures in cold regions is frost resistant.

Due to varying geology, notably large differences have been noted in the water chemistry of rivers around the world. Dissolved minerals from weathered bedrock, woods, and fields together with (acidic) rain and naturally dissolved CO₂ in water can influence water composition and pH. Since measurements began in the 1920s, the pH of major Swedish rivers has varied between 6 and 8 [3,4]. The corresponding values for Norwegian rivers are 5 and 7 [5,6].

Mineral concentrations in Swedish rivers are generally low compared with rivers in Europe, North America and Asia. For example, the average Ca concentrations in the latter cases vary between 18 and 31 mg/l [7]. In many major rivers in northern Sweden, the yearly average Ca concentration is less than 5 mg/l [4]. Concentrations of Ca and Mg are often used to characterise soft versus hard water. Most river water in Sweden is therefore regarded as soft water.

2.2. Chemical degradation of concrete

It is well known that cementitious materials are not thermodynamically stable in contact with soft water. Portland cement concrete is easily attacked by soft water and acidic solutions with low pH. Compounds with alkali elements, such as Na and K, are quickly leached out when concentration gradients are present [8]. Consequently, the pH of the concrete pore solution drops from approximately 13.5 to 12.5, at which point the solution is in equilibrium due to the buffering effect of solid calcium hydroxide (CH).

CH and calcium silicate hydrate (C-S-H) are volumetrically the two most important solid phases in Portland cement paste. In a well-developed paste with a water-to-cement ratio (w/c) of 0.5, C-S-H occupies approximately 50% of the volume, and CH occupies approximately 15% [9]. The remaining volume is occupied by the other hydrates (ettringite and monosulphate; the latter are also referred to as AFt and AFm phases), voids, and remnants of unhydrated cement grains.

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