Cement and Concrete Research 92 (2017) 110–120

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Concrete alteration due to 55 years of exposure to river water: Chemical and mineralogical characterisation

Martin Rosenqvist [a,*], Alexandra Bertron [b], Katja Fridh [a], Manouchehr Hassanzadeh [a]

[a] Division of Building Materials, Lund University, Lund, Sweden
[b] LMDC, Université de Toulouse, INSA, UPS, France

ARTICLE INFO

Article history:
Received 10 June 2016
Received in revised form 24 October 2016
Accepted 9 November 2016
Available online xxxx

Keywords:
Concrete [E]
Portland cement [D]
Long-term performance [C]
Characterisation [B]
EPMA

ABSTRACT

This article presents a study on concrete alteration mechanisms due to 55 years of exposure to river water. Many hydro power structures in cold regions suffer from concrete deterioration at the waterline. Progressive disintegration of the concrete surface leads to exposure of the coarse aggregate and eventually the reinforcing steel. Concrete cylinders drilled out at four vertically different locations on the upstream face of a concrete dam were analysed by electron microprobe analysis, X-ray diffraction, thermogravimetry and scanning electron microscopy. Long-term exposure to the river water, which is regarded as soft water, has led to chemical and mineralogical zonation of the cement paste. Up to five zones with different chemical and mineralogical composition, parallel to the upstream face, were observed in the outermost 8–9 mm of the concrete. Decalcification, precipitation of secondary ettringite and the formation of a magnesium-rich silica gel constitute the major changes that define the zones.

1. Introduction

Many hydro power structures in cold regions suffer from concrete deterioration at the waterline [1–3]. Swedish hydro power plants are one example of such structures. Over the long term, progressive disintegration of the concrete surface leads to exposure of the coarse aggregate and later the reinforcing steel. Ultimately, surface deterioration of concrete may lead to reinforcement corrosion and reduced structural integrity.

Superficial damage at the waterline can be caused by chemical, physical and mechanical processes. Surface deterioration at the waterline of Swedish hydraulic structures in contact with soft water is believed to be caused by interactions between leaching, frost action and (ice) abrasion [4]. The study showed that leaching of calcium compounds significantly amplifies the effects of frost action and abrasion on the rate of surface deterioration. Concrete mixes with and without air entrainment behaved similarly in the tests.

The impact of river water on the chemistry of concrete is complex due to the varying types and concentrations of ions present in the water. Dissolved minerals from weathered bedrock, woods and fields, along with (acidic) rain and naturally dissolved CO_2 in water, affect the chemical composition and pH value of river water [5]. Hence, the water chemistry of the water body concerned has a great effect on the ability of concrete to resist deterioration due to frost action and abrasion.

It is well known that Portland cement paste is not thermodynamically stable when in contact with pure or soft water. Concentration gradients between the external water and the pore solution of the concrete cause diffusion and subsequent dissolution of hydration products [6,7]. In general, dissolution of calcium hydroxide (CH) increases the macroporosity, whereas decalcification of calcium silicate hydrates (C-S-H) increases the microporosity [8,9]. Consequently, long-term exposure to leaching may significantly alter the concrete surface properties.

The possible deterioration of concrete at the waterline begins with leaching of the surface. As the average pore size increases due to leaching, more pore water becomes freezable because nucleation of ice crystals becomes easier as the pore size increases [10]. The concrete surface thus becomes more susceptible to frost action. During the winter and spring, the surface layer is damaged by frost action and possibly later removed by ice abrasion. Then, the process begins again, and surface deterioration continues. To ensure long service life of hydraulic structures, such as concrete dams, harbours, canals and bridge columns, a better understanding of the effects of river water on the deterioration of concrete is required.

The objective of this study was to characterise chemical and mineralogical changes related to the alteration of a concrete buttress dam after 55 years of exposure to the water of the Ångermanälven River in northern Sweden. Concrete cylinders were drilled out at four vertically different locations on the upstream face of the dam; above the normal water level (−1 m), at the water level (0 m) and far below the normal

* Corresponding author.
E-mail address: martin.rosenqvist@byggtek.lth.se (M. Rosenqvist).

http://dx.doi.org/10.1016/j.cemconres.2016.11.012
0008-8846/

water level (10.5 and 18.5 m); see Fig. 1a. As expected, exposed aggregate was visible at the waterline; see Fig. 1b. Far below the water level, the concrete surface was intact because the upstream face has not been exposed to frost action or ice abrasion due to a reservoir water temperature above freezing.

In the laboratory, chemical and mineralogical modifications of the cement paste were analysed with an electron microprobe (EPMA), an X-ray diffractometer (XRD), a thermogravimetric analyser (TGA) and a scanning electron microscope (SEM) combined with an energy dispersive X-ray spectrometer (EDS).

2. Conditions at the dam site

2.1. Concrete dam

The concrete buttress dam considered in this study was constructed between 1954 and 1958. The cement content of the concrete in the upstream face was 330–350 kg/m^3. The water to cement-ratio (w/c-ratio) was approximately 0.5. The aggregates consisted of natural sand and gravel composed of gneiss, schist and limestone. Small amounts of sandstone, greywacke and breccia were also used. The maximum aggregate size was 80 mm.

A low-heat Portland cement was used as binder. The cement had been developed in the 1930s to reduce the concrete's heat evolution during hydration and to improve its resistance to calcium leaching by enrichment in silica. These objectives were achieved by increasing the content of C_2S and decreasing the amount of C_3S. Hence, less calcium hydroxide forms during hydration. The average chemical and clinker composition of the cement are presented in Table 1 [11–14].

2.2. Environmental conditions

In northern countries, the climate varies greatly throughout the year. Air temperatures reach as low as −30 °C and can persist for several days or weeks during the winter months, and most fresh water bodies are covered with ice. Even when surface water temperatures are slightly above freezing, a band of ice frozen solid to the concrete surface can be observed at the waterline [15]. The formation of ice on concrete surfaces in contact with unfrozen water indicates that freezing temperatures occur in the concrete.

Ice covers break up in spring, and ice sheets may push against the structures and cause abrasive wear to the concrete surface at the waterline (denoted normal water level in Fig. 1) [4]. If the surface layer is frost damaged and removed, a new surface is exposed to leaching, and the deterioration process restarts. Hence, continuous degradation of the concrete surface at the waterline results in exposure of the aggregate and ultimately the reinforcing steel.

Far below the normal water level, the upstream face is not exposed to either frost action or (ice) abrasion because the temperature of the reservoir water is above freezing. Instead, the dam is subjected to hydrostatic pressure, forcing water into the concrete.

Exposure classes and corresponding limiting values for various aggressive environments to which concrete may be exposed are defined in EN 206 [16]. Depending on the location along the upstream face, the dam is exposed to varying degrees of freeze/thaw attack (XF) and chemical attack (XA). The latter depends on the river water chemistry.

2.3. River water chemistry

Chemical analysis of Ångermanälven River water has been conducted at the river mouth, approximately 100 km downstream from the dam, monthly since 1969 [17]. Table 2 presents the average concentrations and standard deviations of Ca, Si, Al, Fe, Mg, Na, K and SO_4 ions. The table also shows the pH value and the amount of naturally dissolved CO_2 in the river water [18] and limiting values for a slightly aggressive chemical environment (XA1). By comparing the limiting values with the results of the chemical analyses of the river water, it can be concluded that the river water does not fulfil the conditions for XA1. However, the river water can be regarded as soft water due to its low concentrations of ions, particularly calcium and magnesium ions. The hardness of the water is also presented in Table 2.

As mentioned in the introduction, soft water can have a detrimental effect on the durability of concrete. Chemical and mineralogical characterisation of concrete specimens from different locations on the upstream face of the dam provide information on the effects of leaching, frost action, ice abrasion and hydrostatic pressure on the alteration of the cement paste.

3. Experimental work

3.1. Specimen sampling

Concrete cylinders measuring 74 mm in diameter and 300 mm long were drilled out at four vertically different locations on the dam. The cylinders were drilled out perpendicular to the upstream face with the help of divers. The four locations are marked with black dots in Fig. 1a, including the distance to the normal water level. In addition to delineating the waterline (0 m), locations 1 m above the normal waterline and at water depths of 10.5 and 18.5 m were marked. The cylinders were immediately brought to the surface and wrapped in plastic foil to prevent the concrete from drying. In this study, cylinders from the waterline (0 m) and from far below the water level were used to characterise chemical and mineralogical changes of the cement paste.

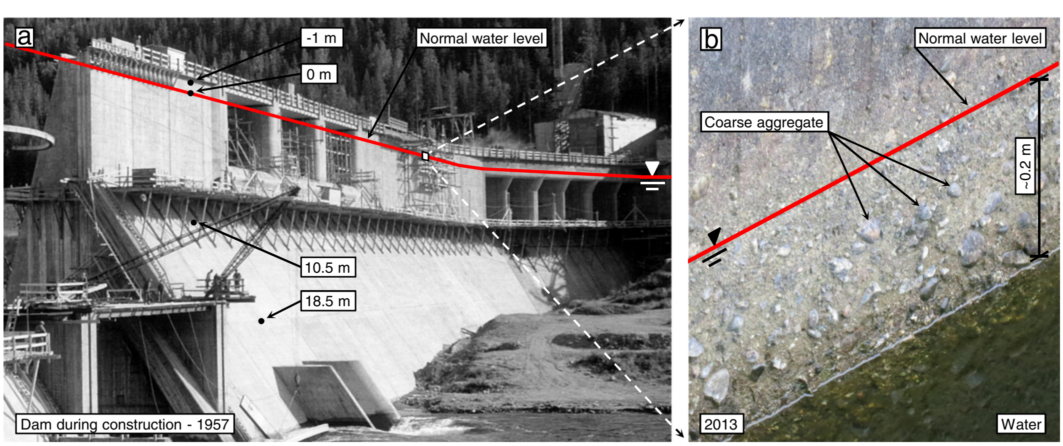

Fig. 1. Upstream face of the concrete buttress dam during construction (a). Black dots mark the locations of the concrete cylinders and the distances to the normal water level. Today, coarse aggregate is exposed at the waterline (b).