



## Determining the free alkali metal content in concrete – Case study of an ASR-affected dam

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### ABSTRACT

In concrete affected by alkali–silica reaction (ASR), aggregates react in the high pH environment and cause deleterious expansion and cracking of the concrete. Leaching of alkali metals from the concrete might therefore locally reduce ASR. However, few data on alkali metals leaching are available in the literature. Our goal was to document the alkali metal leaching and to build-up an alkali inventory (the amount in solid and in solution, and the amount released by the aggregates) in a full-scale structure, the 50-year-old Votna I dam in Norway. Free alkali metal profiles were determined on cores taken at four locations with different exposure conditions: permanently immersed, periodically immersed, exposed to rain, or sheltered. Alkali leaching was observed at all four locations up to a depth of 100 mm. The leached zone exhibited less intense cracking than the non-leached concrete, indicating that the alkali leaching might be limiting ASR.

### 1. Introduction

Alkali–Silica Reaction (ASR) is one of the major deterioration mechanisms for concrete. Three conditions need to be fulfilled for ASR to take place: i) the presence of reactive aggregates, ii) a high pH in the pore solution, and iii) a high moisture content, i.e. above 80% relative humidity [1, 2]. If all three conditions are met, an expansive silica-rich gel can form which can lead to concrete expansion and cracking.

The pH of the pore solution of concrete typically ranges between 12.5 and 14 [3–5]. The pH is buffered up to at least 12.5 because the pore solution is saturated with respect to portlandite (Ca(OH)<sub>2</sub>). The presence in the pore solution of alkali metal ions such as Na<sup>+</sup> and K<sup>+</sup> raises the pH above 12.5. The alkali metal ions are critical for the high pH levels required for ASR to take place. The pH required depends on the type and reactivity of aggregate [6]. This is reflected in the regulations that limit the alkali metal levels in concrete made with potentially reactive aggregates [7].

The alkali metals (Na and K) in the pore solution originate primarily from the constituents of the concrete – mainly from the cement, but release from the aggregates has also been reported [8, 9]. Alkali metal ions can also come from additives and external sources, such as sea-water and de-icing salts, which penetrate the concrete. However, this ingress of Na<sup>+</sup> and K<sup>+</sup> is limited compared to Cl<sup>−</sup> [10, 11]. Yet, alkali metal ions can also exit the concrete by leaching to the exterior.

This study focuses on alkali metal leaching from concrete, which has

been extensively investigated in laboratory samples. Leaching of up to 100% of the total alkali metal content has been observed for submerged concrete prisms [12] and of 10–35% from samples stored above water for one year [12, 13]. The extent of leaching depends on: the storage conditions [12, 14], the specimen size [12, 15], the initial alkali metal content [12, 16], and the binder type [12, 13]. It has been demonstrated that alkali metal leaching from concrete prisms leads to reduced expansion during ASR performance testing [12, 14, 17].

There have, however, been very few studies on alkali metal leaching in real structures [18–20]. One reason is that it is difficult to extract pore water from old concrete by expression under pressure. Grattan-Bellew and Danay [18] and Bérubé et al. [19] investigated Canadian dams that were 50 to 75 years old. They measured the free alkali metal content of concrete cores using an alternative method to extraction under pressure: the hot water extraction method. This is a leaching method where the samples are pulverised, mixed with boiling deionised water for 10 min, and cooled overnight. In these studies, however, it was not possible to determine detailed alkali metal profiles, due to either a large sample size or a large spacing between the samples. Moreover, the exposure conditions were not clearly specified. It is therefore difficult to draw conclusions about the impact of the exposure conditions on the alkali metal leaching. Kagimoto et al. [20] succeeded in extracting pore solution at high pressure from concrete cores taken from a 14-year-old dam. The pore solution near the surface (in this case, the first 100 mm) exhibited a lower alkali metal concentration than at

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greater depth in the concrete. Again, the exposure conditions were not clearly stated, which limits any potential generalisation of the results.

This paper presents an investigation of the influence of the environmental exposure conditions on the alkali metal leaching from the ASR-affected concrete dam, Votna I, situated in south-western Norway. Four 500–700 mm long cores were extracted from selected locations. We applied the cold water extraction method (CWE), which is a rapid leaching method [5], on 10 mm thick slices to determine the free alkali metal profiles in the concrete. Those cores go through the entire length of the structure in order to investigate the external and internal conditions of the dam. In addition, potassium profiles were determined using a micro-XRF. Thermogravimetric analysis was applied to investigate the variations in the cement paste-to-aggregate ratio in the 10 mm slices. On four parallel cores, 50 mm slices were split off to determine water content, degree of capillary saturation, and relative humidity profiles. The water content was used to calculate the pH of the pore solution based on the free alkali metal content. Furthermore, cracking density profiles were determined on additional four parallel concrete cores using image analysis on fluorescence-impregnated plane-polished sections. The leached outer zone, with a depth of up to 100 mm in the permanently submerged core, exhibited less extensive cracking than the non-leached zone. Finally, the release of alkali metals from the aggregates to the concrete was evaluated based on the CWE results.

## 2. Materials and methods

### 2.1. The Votna I Dam

Four concrete dams were constructed between 1964 and 1966 in the Votna area of Norway. This study focuses solely on the dam called Votna I. It is a double-curved arch dam connected to a slab dam via an abutment wall (Fig. 1 and Fig. 2). The dam's total length is 185 m and its maximum height is 55 m. The thickness of the arch dam is 4 m at the bottom decreasing to 0.95 m at the top. The slab dam has a thickness of 0.7–0.8 m at the bottom and 0.3 m at the top. This study focused on the slab dam. The water level in the reservoir reaches the top of the dam during summer/autumn and is gradually lowered during winter/spring. The composition of the water in the reservoir is given in Table 1 (data retrieved in February 2017).

The concrete mix-design used for the slab dam is given in Table 2. The composition can slightly differ from one location to another. No data has been found for the concrete used in the pillars. According to the owner, Hydro Energy AS, a lower quality concrete with a lower cement content was used for the pillars. This was confirmed in an

earlier study on the Votna II slab dam cast in the same period [21]. The sand used was a granite gneiss from Nesflaten, Norway, and the coarse aggregate was a local cataclastic crushed rock. It is the coarse aggregate which is classified as potentially ASR reactive [22]. The coarse aggregate was extracted from the concrete using the method described in the section 2.2 and was analysed by XRF, using a Bruker S8 Tiger, 4 kW X-ray spectrometer. The composition of the coarse aggregate is given in Table 1. No documentation is available on the cement, but considering the period of construction, i.e. 1964–1966, a pure CEM I is thought to have been used. The statistics from the Norwegian Norcem Dalen cement factory indicate that the alkali metal content in the CEM I cement of that period was between 1.19% and 1.28% [23].

The first indications of ASR in the dam were observed in the years 1987–1988, with typical map cracking in the arch dam coupled with deformations at the top. Votna I has been investigated several times since then, with regular deformation measurements, safety evaluations and laboratory investigations of drilled cores for moisture measurement, “Crack Index” determination, gel observation, and the testing of mechanical properties. The results of these studies have been presented [21, 24], but the free alkali metal content of the concrete has never been investigated. Larsen et al. [21] confirmed that ASR was the cause of the damage observed and concluded that the reaction was still in an early stage. The deformation caused high stress concentrations in the structure at the connection point between the arch dam, the slab dam, and the abutment wall (Fig. 1). Repair works were undertaken during the summer of 2015 by cutting out part of the slab dam and the abutment wall over their entire height (about 15–16 m) to release the compressive stresses: about 1 m width for the slab dam and about 0.5 m width for the abutment wall (Fig. 3-f). These repairs meant that the water reservoir had to be completely emptied, which gave a unique opportunity to drill concrete cores from locations usually not accessible.

The structure was inspected in May 2015. Fig. 3-a and -b show the typical ASR map cracking, Fig. 3-c shows the presence of gel, and Fig. 3-d illustrates the highly humid atmosphere inside parts of the slab dam structure. Aggregates are visible on the usually submerged surface of the concrete of the slab dam (Fig. 3-e). The locations for the drilling of the cores were decided during the inspection of May 2015 (Fig. 3-f). Each location corresponds to a different exposure condition, and therefore we expect a difference in alkali leaching, which can influence the extent of ASR. Fig. 1 shows the various drilling locations, called W, WA, A, S and E. Location W corresponds to the bottom part of the slab dam, normally submerged in water. Location WA is in the top part of the slab dam, which is either submerged in water or exposed to atmospheric conditions (e.g. rain, snow, ice, sun) depending on the level of the reservoir. Location A corresponds to the “outside” pillar of the

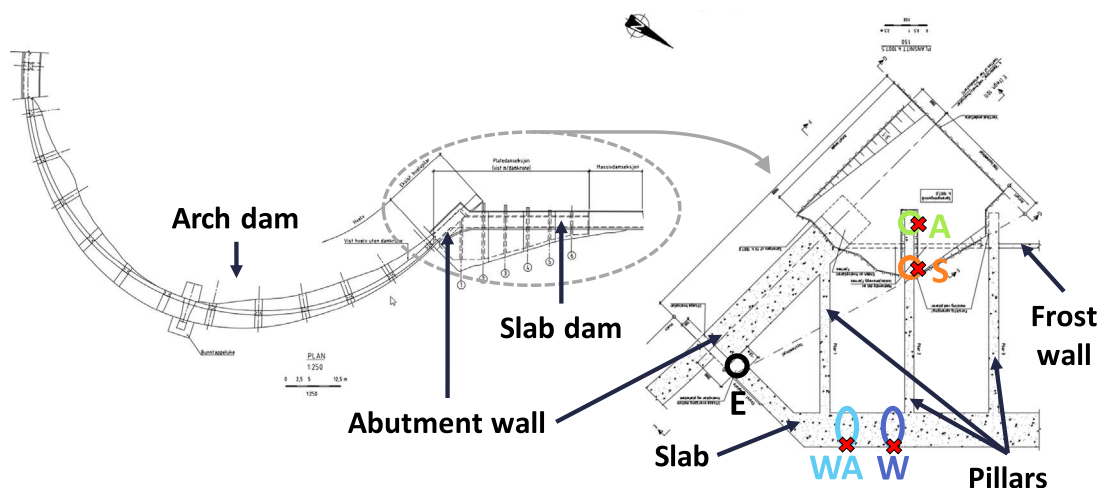


Fig. 1. Sketch of the Votna I dam (top view) and location of the different cores (see Table 3). The crosses indicate the reference surface of the cores. The arrow at the top points north. Provided by Hydro Energy AS.

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