EXPERIENCES FROM EXTENSIVE CONDITION SURVEY AND FEM-ANALYSES OF TWO NORWEGIAN CONCRETE DAMS WITH ASR

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Abstract

Even though alkali silica reaction (ASR) is one of the main deterioration mechanisms in Norway, only a few Norwegian concrete structures with ASR have so far been rehabilitated. As a basis for planning and executing repair works, detailed condition surveys including laboratory analyses are required in order to diagnose the cause of damage, to evaluate the extent of damage over the structure and as a basis for calculating the remaining load capacity.

This paper presents the experiences from an extensive condition survey and FEM-analyses of two about 40 years old Norwegian concrete dams with ASR, one slab concrete dam and one arch dam. The background for the project was that the slab in the mid corner of the slab dam suddenly lifted from the supporting pillar due to expansion. In 2006 this slab concrete dam was rehabilitated, and in 2008 a monitoring program is planned to be established.

Keywords: alkali silica reaction, slab concrete dam, condition survey, repair

1 INTRODUCTION

1.1 Background

Most concrete dam structures in Norway were built before 1980. Norwegian regulations to prevent damage due to alkali silica reactions (ASR) were, however, not introduced until the early 1990'ties when the ASR problem was recognized as a durability challenge also in Norway. During the recent years ASR have been documented in an increasing number of concrete structures, and ASR is now regarded as one of the main deterioration mechanisms in Norway.

So far, only a few Norwegian concrete structures suffering from ASR have been repaired. As a basis for planning and executing repair works, detailed condition surveys are required. As part of such surveys relevant laboratory analyses have to be executed, both in order to diagnose the cause of damage, to evaluate the extent of damage over the structure, and for calculating the remaining load capacity of the structures.

This paper presents the experiences from an extensive condition survey and FEM-analyses of two about 40 years old Norwegian concrete dams with ASR, one slab concrete dam (Votna 2) and one arch dam (Votna 1). The background for the project was that the slab in the mid corner of the Votna 2 dam suddenly lifted from the supporting pillar due to expansions caused by ASR and temperature.

The project has been led by SWECO Grøner. This consultant company has also performed all the structural calculations and evaluations, in addition to planning the rehabilitation works on the Votna 2 dam executed during the summer season 2006. SINTEF Building and Infrastructure has performed all the laboratory investigations of the drilled concrete cores, in addition to taking part in the condition survey and the evaluation of the extent of damage of the concrete dams.

1.2 Main information of the Votna dam structures

The Votna dams, owned by Hydro Energy Production AS, consist of 4 concrete dams located in the same area and constructed in the years 1964 to 1966. The main dam, Votna 1 (Figure 1 and 2), is a double curved arch dam with a total length of 185 m. The maximum height is 55 m and the thickness increases from from 0.95 m in the top to 4.0 m in the bottom part. The Votna 2 dam (Figure 3) is a slab concrete dam with a maximum height of 20 m and a total length of 230 m. The thickness of the slabs varies from 0.30 to 0.80 m (thickest in the bottom part). The distance between

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the pillars supporting the slabs is 5 m. The two other dams at Votna are smaller gravity dams creating the spillway sections.

The Votna dams are situated in the south-western part of Norway 950 metres above sea level, and forms the intake reservoir for the Novle Power Plant. The reservoir is normally regulated about 20 m every year, with a high water level during the summer/autumn seasons and a low water level during the winter time.

1.3 Development of ASR in the Votna dams - review of the main events

In 1987-1988 the dam owner got the suspicion that an alkali aggregate reaction was going on in the concrete. Typical map cracking was observed in the arch dam (Votna 1), and the deformation measurements at the top of the arch dam showed abnormal results.

An investigation of the concrete in the arch dam confirmed that ASR had started. The outcome of a comparison between the observed abnormal deformations and a simple FEM-analysis was that the swelling of the concrete had taken place since 1980, and that the reaction during 10 years (1980-1990) had resulted in a swelling of the concrete of a magnitude of 0.44‰.

In 1997 a review of the safety of the Votna dams was performed according to the normal Norwegian regulations for dam safety. This review concluded that more investigations and analyses should be performed before conclusions regarding the dam safety could be drawn.

In the years 1990–2003 the deformation of the top of the arch dam was measured regularly once a year, and the results show that the expansion of the concrete is increasing linearly with time.

During a normal dam visit in May 2003 the dam owner discovered an alarming happening in the corner of the slab concrete dam (Votna 2), where the dam has a change of direction of about 22°. At the pillar in the corner and the two neighbour pillars the front slab had been lifted away from the pillars – see Figure 4. At the top of the dam there was a gap of about 50 mm between the pillar and the front slab. This gap decreased towards zero at the bottom of the dam. The cause of this movement was expansions of the slab. Without being noticed by the owner, the slab had expanded due to ASR leading to closed joints between the slab elements (each with a length of about 10 m). Thus there was no more space for expansion of the slabs when the temperature of the concrete increased on a warm sunny day with a low water filling of the magazine (about 15 m below the maximum approved water filling level).

In the following years (2003–2006) condition surveys, laboratory investigations of drilled concrete cores, dam safety evaluations, and planning and execution of rehabilitation work of the slab concrete dam (Votna 2) were performed.

A condition survey and laboratory investigations of drilled concrete cores were also performed for the arch dam (Votna 1) as basis for new dam safety evaluations that was initiated in 2005. However, the conclusions of this safety review are not yet finalized.

2 CONDITION SURVEY, SAMPLING AND LABORATORY ANALYSES

2.1 Condition survey - sampling

The visual inspections have showed that map cracking occurs on both dams. However, the extent of cracking over the structures varies a lot. On the arch dam (Votna 1 - see Figure 2) the most pronounced map cracking was observed in the railing (concrete wall). Expansion of the arch dam is also documented over several years by deformation measurements in the top.

For the slab concrete dam (Votna 2) the most extensive map cracking was observed on the downstream face of the slab (behind the frost protecting wall), but no precipitation of calcium carbonate was observed, indicating no continuous cracks through the slab from the water side. Severe expansion of the slab has been observed, as described in section 1.3. Map cracking was also observed in the upper parts on the railing (concrete wall) and the most exposed areas of the unsheltered parts of the pillars (see Figure 3). No signs of ASR were observed in the sheltered parts of the supporting pillars inside the frost protection wall.

In 2004 SINTEF participated together with the consulting engineer and the owner in the survey of the two dams, during which the number and location of samples were agreed upon. No detailed instructions were given to the drilling contractor with respect to the exact location of each core in relation to possible surface cracks. All together more than 100 concrete cores (diameter 100 mm, length 160-490 mm) were drilled from the following main parts of the dams: 1) The upper and lower parts of the arch dam (Votna 1; drilled from the top and the downstream face), 2) The pillars of the slab dam (both sheltered and not sheltered areas) and 3) The upper, middle and lower part of the slab of the slab dam (Votna 2; drilled from the downstream face).

2.2 Laboratory analyses of drilled concrete cores

General

The laboratory investigations of the drilled cores included measurements of moisture content, material structural analysis and mechanical properties. The laboratory analyses performed are among the assortment of methods described by RILEM in their new recommendations for condition survey of concrete structures suspected to suffer from ASR [1]. Table 1 shows the number of the different laboratory analyses carried out by SINTEF.

Moisture content

The drilling procedure at the site included actions to prevent loss/supply of water from/to the concrete cores during drilling. It was specified that the cores should be wiped off and sealed in plastic bags immediately after drilling. The inner part (length approx 50 mm) of approximately 30 concrete cores were split off in the laboratory immediately after un-wrapping and weighed in different moisture conditions. The degree of capillary saturation (DCS) was calculated according to Equation (1) [2].

$$DCS = \frac{\text{Weight in situ - Weight after drying at } 105°C}{\text{Weight after immersion in water - Weight after drying at } 105°\text{C}} \qquad (1)$$

Weight in situ = Weight measured in the laboratory on "undisturbed" field samples (i.e. on samples with a moisture content that is supposed to represent the moisture state in the structure).

The depths of the samples varied between 100 and 500 mm from the concrete surface (top or downstream). The results are presented as mean values for different structure parts in Table 2.

Material structural analyses

The material structural analysis included an initial visual inspection of the concrete cores with emphasis on presence and character of cracks and possible precipitations in the air voids. In the next step the concrete core were divided into two parts by sawing in the length direction. One of the halves was used to produce a plane polished section, impregnated with fluorescent epoxy, for macroscopic investigations in UV light (i.e. presence and extent of cracks, aggregate origin (crushed or natural), air distribution and possible reacted aggregates/reaction products). The extent of cracks in the plane polished sections was determined according to a "Crack Index" method. In this method the number of coarse aggregates containing cracks continuing from the aggregate into the cement paste (given as volume %) and the number of cracks in the cement paste (given as number/cm^2 multiplied with 100) were counted. A "Crack Index" (CI) was then calculated by giving different weight to each parameter counted [3]. This method is a simplified version of the DRI-method [4].

From the second half of the concrete cores one thin section was prepared and examined by use of a polarizing microscope with UV filters. By use of this microscope it is possible to detect the w/b-ratio, the air content, the rock types, any reacted particles, and the presence of any cracks and/or precipitations. In order to give a precise diagnosis of any presence of ASR, it is required to detect alkali gel during the thin section analysis. When evaluating if and to what extent ASR appears in the samples, special attention is paid on investigating whether the ASR forms cracks within the aggregates and in the cement paste.

The Crack Indexes are summarized in Table 2, as mean values for the different structure parts. A photo of a plane polished section with Crack Index 12.5 is shown in Figure 5 and a photo of a thin section showing clear signs of ASR is shown in Figure 6.

Mechanical properties

The compressive strength was determined according to EN 12390-3 for ø100 mm cylinders with lengths varying from 100 to 200 mm,. The results were recalculated to compressive strengths corresponding to specimens with a length/diameter ratio of 2.0.

The static E-modulus was determined for ø100 mm x 200 mm cylinders according to NS 3676, which is a modified version of ISO 6784.

The splitting tensile strength was determined for ø100 mm x 120 mm cylinders according to EN 12390-6.

The dynamic E-modulus was determined on all cylinder specimens with lengths 120 mm and 200 mm, respectively. According to ASTM C215-02 the minimum length/diameter ratio should be 2.0, and a comparison of results should only be performed between specimens with the same length. It was, however, decided to carry out the tensile splitting of the smallest specimens as well, in order to possibly detect internal differences within the same length category. No significant differences were however detected between the two length categories, and the mean values were calculated based on all results.

All results from the testing of mechanical properties are presented in Table 2, as mean values for different structure parts.

2.3 Discussion

Degree of capillary saturation (DCS)

The lowest values for DCS were found in the pillars sheltered from precipitation, with a mean value of 87 %. The water content in the other parts of the two dams was higher, the mean values varying from 91-95 %. Earlier experiences [5] have demonstrated that concrete with damaging ASR almost without exceptions have DCS-values above 90 %, and that the most severe damages are observed in parts of concrete structures with DCS above 95 %. In this study, however, no significant increase in crack indexes (CI) was found with increasing DCS above 90 %.

Material structural analyses

The material structural analyses document that the cracking and expansion of the concrete in the two dams are caused by ASR. The thin section analyses documented that the coarse aggregate in all the concrete cores was a crushed cataclastic rock, classified as alkali reactive in Norway.

There are large variations in the measured Crack Index (CI), varying from 0.7 – 15.0. A comparison of visual observations in field and in the material structural analyses with the measured Crack Indexes (CI) shows that cores with CI less than 2 have “no” or “small signs” of ASR. Cores with CI in the range 2-7 show “signs” of ASR, while all the cores with CI higher than 10 show “clear signs” of ASR. Even the cores with the highest CI are however evaluated to be in an early stage of damage. The dam structures are about 40 years, and this demonstrate that the material degradation rate is rather low. This is probably due to a combination of the rather slow reactivity of Norwegian aggregates and the low average temperature in the Norwegian mountain areas.

All the lowest values (CI<2) were measured on samples from pillars (both sheltered and not sheltered parts), while one sample from a not sheltered pillar had CI=4. The low CI measured in the supporting pillars and the fact that no signs of ASR was observed in the sheltered parts of the pillars inside the frost protection wall are assumed to be due to two reasons: 1) The water content of the sheltered parts is too low for ASR to initiate and 2) The alkali content of the concrete in the pillars is probably lower than in the arch/slab parts as the prescribed concrete quality is lower for the pillars. This is also confirmed by lower measured compressive strengths on the cores drilled from the pillars (see below).

The cores from the upper part of the slab had higher crack intensity (average CI=14) compared to other structure parts. This is probably due to the fact that this part of the dam is less restrained compared to lower parts of the slab and the arch, i.e. the concrete has easier access to expand.

Mechanical properties

The mean compressive strengths in the arch dam (48 MPa, 18 specimens) and the slab (46 MPa, 9 specimens) are somewhat higher than in the pillars (38 MPa, 15 specimens). As the concrete in the arch and the slab is of the same prescribed quality and composition, the results from these structure parts have been treated as one test series during statistical calculations. Equivalent characteristic cylinder strengths, f_{cck}, are calculated according to NS 3473:2003 to 36 MPa for the pillars and 41 MPa for the arch/slab, indicating that the concrete in both cases satisfy the strength class B35 in EN 206-1.

The mean value for the static E-modulus, Ec, is calculated to 25 GPa for the pillars (2 specimens) and 22 GPa for the arch/slab (10 specimens), respectively. This is considered to be in the lower normal area of concretes with the actual measured compressive strengths, especially for the arch/slab which have the highest compressive strengths. The effect of the ASR may be present in the measured E-modulus.

The mean splitting tensile strength is calculated to 4.1 MPa for the pillars (11 specimens) and 4.2 MPa for the arch/slab (19 specimens), respectively (specimens with clear surface cracking are not included). According to NS 3473:2003 the centric tensile strength can be calculated as 2/3 of the splitting tensile strength, e.g. in this case 2.7 MPa and 2.8 MPa, respectively. These values are lower than expected from the compressive strength results. This may, however, be due to the fact that the increase in tensile strength with time is less than the increase in compressive strength. A possible influence from internal cracking due to ASR should neither be excluded.

No clear relation is found between the measured dynamic E-modulus and the observed cracking of the concrete in the same structure parts. There is, however, a slight tendency of lower measured E_{dyn} in the locations with the clearest signs of ASR.

3 INVESTIGATIONS, EVALUATIONS AND REHABILITATION OF THE SLAB CONCRETE DAM, VOTNA 2

3.1 Safety evaluations

Between each front slab element with length about 10 m there is a vertical expansion joint. The nominal width of these joints was 10 mm at the time of construction. Based on the observed closing of several of these joints the maximum expansion of the concrete in the top of the front slab was estimated to be about 1 ‰. This is in good agreement with the measured expansion of the arch dam (Votna 1) built in the same period with an identical concrete composition (see section 1.3).

Based on the measured material properties of the drilled concrete cores (see sections 2.2 and 2.3), calculations of stresses and remaining structural capacity were performed. In the ultimate state the calculated moment capacity of the slab showed only a small reduction due to ASR. Thus, the moment capacity is evaluated to be satisfactory in the present situation and also for the coming 25 years. Our evaluation is that the reinforcement in this period will not have any reduced capacity even though ASR is present in the concrete dam.

The situation in the state of serviceability is, however, more uncertain. The reinforcement may, during the coming 25 years, reach a situation of more than 2 ‰ expansion, which is the yielding point. The bearing capacity of the slab elements with respect to shear forces was also found to be unacceptable. The background for this evaluation is the measured tensile strengths on the drilled concrete cores and the fact that the Norwegian standard for evaluation of shear capacity has been changed conservatively after the dam was designed.

A normal effect of ASR appearing in the concrete is that the strength of the concrete will be reduced with time, in particular the tensile strength. As the shear capacity is dependant on the tensile strength, also the shear capacity in assumed to decrease with time. This is the main background for the decision made to strengthen the front slab of the dam. Another influencing factor was sabotage consideration. After evaluation of different repair methods, it was concluded to construct a new front slab on the upstream face of the existing front slab.

It is uncertain whether the new slab will reduce the speed of the on-going ASR in the old concrete slab. It the moisture content in the slab is lowered during the coming years, a slight reduction on the rate of deterioration is expected.

3.2 Provisional measures

In June 2003, when the alarming damage on the slab concrete dam was discovered, the water level was about 15 m below the maximum approved water filling level. It was immediately introduced a restriction of the maximum water filling level in the reservoir. In addition several provisional measures were undertaken.

The gap between the front slab and the supporting pillars at the corner part of the dam was immediately filled with mortar. However, on one occasion where the workers stayed inside the dam, the slab suddenly lifted even more from the pillars followed by a frightening high sound.

Later on the vertical joints between the front slab elements on the most affected parts of the dam were cut open by use of a diamond saw, to a width of approximately 45 mm. In addition a new concrete slab with a length of about 20 m was concreted upstream at the angular point (i.e. the "problem corner") of the dam – see Figure 7. In order to allow free movement between the old and the new slab, a membrane was applied before casting the new slab. These provisional measures have later become a part of the permanent rehabilitation of the slab concrete dam.

3.3 Permanent rehabilitation works

The following permanent rehabilitation works were carried out during the summer 2006:

- The old slab had expanded so much due to ASR that most of the joints between the slab elements had been closed over the years. Thus all the joints in the old slab were cut open from top to bottom by use of a diamond saw (to a width of approximately 45 mm) to give room for expansion during temperature rise in the summer season, in addition to allow more expansion due to further development of the ASR in old slab concrete.
- A new concrete front slab was concreted upstream the old slab over the total length of the dam. The new slab was divided into slab elements with length 10 m separated with expansion

joints located at every second supporting pillar (the joints between the old slab elements were located between the pillars). To seal the joints a "water stop" sealing was used (see Figure 7).

- To allow free movement between the old and the new slab (except in the bottom part of the dam height where bond is aimed), a smooth membrane was placed between the slabs.
- A drainage system was established by drilling several holes through the bottom part of the old slab (underneath the lower part of the membrane – see Figure 8). Thus any water leaking through the new slab is allowed to drain through the old slab.
- To create a good bond between the two slabs in the bottom part of the dam steel bolts were placed between the new and the old slab. In addition the surface of the old slab was prepared by general chiselling and sawing of horizontal slots prior to casting.
- The old railing (concrete wall) at the top of the dam was removed, and a new one was concreted. A photo of the rehabilitated dam is shown in Figure 9.

4 INVESTIGATIONS AND EVALUATIONS OF THE ARCH DAM, VOTNA 1

4.1 FEM-analyses

General

For the arch dam, Votna 1, FEM analyses have been performed to analyse the effect of the alkali reaction on the dam structure. The FEM (Finite Element Method) programme ANSYS version 10.0 has been applied for calculation of the displacements, stresses and expansions in the arch. Also the sum of forces acting on the large concrete pillar on one of the side banks of the arch has been calculated, and a stability analysis for this pillar has been performed.

The forces acting on the rock foundation of the arch dam have also been calculated, and stability analysis for the rock mass has been performed.

Simulation of the displacements of the arch due to ASR

At time of construction five steel bolts (named bolt 11-15) for measuring horizontal displacements were mounted on the top of the arch dam. Measurements have been performed systematically since 1966. Figure 10 shows the yearly measured displacement of bolt 12 (bolt 14 located symmetrical on the other half of the arch dam, shows a displacement of the same order). The figure shows that the abnormal displacements started at year 13 (1979), and that the mean yearly displacements since then have been approximately constant. These yearly measurements show that the dam crown gradually has moved towards the upstream face since about 1980.

In the FEM analysis we have tried to find the best load combination in order to simulate the displacements of the five bolts due to ASR. Figure 11 shows the location of the bolts and the calculated horizontal deformations due to a uniform temperature load. The calculated radial deformations due to the same temperature loads are shown in Figure 12. Our conclusion is that the best correlation between the FEM analysis and the measured displacements are obtained when applying the following "loads": uniform expansion of concrete = 0.96 ‰. With these "loads" we obtained a good agreement between the calculated and the measured displacements – see Table 3.

Calculation of stresses and tensions in the arch

Calculations of stresses and tensions in the arch due to the combination of normal load conditions and the effect of ASR were performed as part of the FEM analyses, and capacities in the ultimate limit state were calculated. These evaluations were done both for the area in the mid part of the arch and in the lower part towards the rock foundation. The evaluations are primarily performed for the situation in year 2005. In addition some considerations for the assumed situation in year 2025 are performed. The on-going ASR is assumed to affect the arch dam in the following ways:

- The expansion due to ASR creates what is defined as initial strain and stress. In the reinforcement this initial strain is ε = 0.96 ‰ and the corresponding initial tension is σ = 190 MPa. The corresponding initial stress in the concrete is depending on the amount of reinforcement in the section. With reinforcement percentages varying between 0.13 and 0.39 the equilibrating initial stresses in the concrete vary between -0.24 and -0.74 MPa. Assuming a nominal E-module of about 25 GPa, the corresponding effective initial strain in the concrete varies between -0.01 and -0.03 ‰.
- The arch is fixed at the abutments, and the ASR expansion of the structure gives additional secondary stresses and strains. These are calculated in the FEM analysis.

Capacity in the ultimate limit state

In the mid part of the arch where the stresses due to the water pressure is at a maximum, we have found that the effect of the ASR expansion is opposite the effect of the water pressure. The horizontal normal force is calculated to be 15 200 kN/m and the corresponding capacity is calculated to be 61 800 kN/m. The effect of the ASR expansion is calculated to be $\varepsilon = + 0.28$ ‰, and this will not reduce the calculated capacity of the arch dam.

At the critical areas at the abutments the calculated capacity is 3.2 times the calculated force caused by the water pressure. The effect of the ASR expansion is calculated to give an effective concrete strain $\varepsilon = -0.15$ ‰, only leading to a 1 % reduction of the calculated capacity.

The effect of the ASR expansion is at a maximum at the deepest part of the arch. Here the local maximum effective compressive concrete strain due to ASR is calculated to be $\varepsilon = -1.28$ ‰ (2005). In this part of the arch the stresses due to the water pressure is, however, very low. We expect that concrete strain, $\varepsilon = -3.5$ ‰, will be reached within a timeframe of about 30-40 years.

Review of the stability of the rock foundation

It is well known that the safety of an arch dam is based upon the ability of the rock foundation to transfer the large horizontal forces from the arch into the foundation. The safety of the rock foundation at Votna 1 has earlier been studied with a positive conclusion regarding safety with respect to sliding of the rock masses. This study was however performed before the discovery of the ASR in the dam, and the effect of ASR was naturally not taken into account. Thus a new study was performed.

Restraint of the ASR expansion in the arch has a potential of creating large horizontal forces in the arch in additional to the forces from the water pressure. The build-up of compressive stresses depends on the effective E-module associated with this process. Accelerated laboratory tests with partly restrained specimens indicate low deformation modules, especially if the restraint is acting mainly in one direction. Furthermore, the additional forces from the ASR have a much more favourable direction. These forces act much more perpendicular to the rock foundation than the forces from the water pressure. The conclusion of our evaluation, assuming an unfavourable high E-module of about 25 GPa, is that the safety factor against sliding is 1.6. The minimum acceptable safety factor is 1.25 (Eurocode 7).

Pillar for the arch

On one of the sides of the arch there is a 17 m high arch pillar and a smaller slab concrete dam – see Figure 2. On this side the forces from the arch is not diverted directly to the rock foundation, but via this arch pillar. The ASR in the arch creates additional internal forces as it does for the rock foundation. The stability analysis performed with high E-module shows that this arch pillar does not have a satisfying safety factor with respect to sliding. It is our opinion that the forces will be considerably lower than this first estimate and that the arch has the ability to distribute these forces in an alternative manner directly to the rock foundation, but this has to be documented later in a separate FEM analysis.

4.2 Safety evaluations

The on-going safety evaluations for the arch dam (see section 4.1) has to be finalized before any conclusions are made with respect to life time prediction and planning of any rehabilitation work on the arch dam.

5 CONCLUSIONS

A condition survey including an extensive laboratory programme has been performed on two Norwegian concrete dams with ASR as a basis for performing safety evaluations including FEM-analyses. One of the dams has also been rehabilitated. The following conclusions may be drawn:

- Material structural analyses document that the cracking and expansion of the concrete in both dams are caused by ASR.
- There are large variations in the extent of cracking in the drilled cores. The measured Crack Index (CI), varies from 0.7 – 15.0, representing cores without ASR (low CI) to cores with clear signs of ASR (high CI). The Crack Index even varies a lot within the same location/structure part, showing no clear connection between measured water content and CI.
- The lowest crack intensities are measured on samples drilled from the pillars of the slab dam. This is probably due to two reasons: 1) The water content is partly too low to develop ASR and 2) The alkali content of the pillar concrete is probably lower than in the arch/slab parts.

- There is a tendency to a higher cracking intensity in the upper part of the slab compared to other structure parts. This is probably due to easier access for expansion.
- The measured mechanical properties indicate that the concrete still performs well. No significant differences in the measured compressive strengths, splitting tensile strengths and static E-modulus were found within each main structure part. There is, however, a slight tendency of lower dynamic E-modulus in the structure parts with the clearest signs of ASR. The tensile strength is lower than expected from the compressive strength results. This may be due to the fact that the increase in tensile strength with time is less than the increase in compressive strength. A possible influence from internal cracking due to ASR should neither be excluded.
- Due to the fact that the documented ASR is regarded to be in an early stage, it must be taken into account that the expansion and cracking will continue. This may lead to a reduction in the mechanical properties with time, the tensile related properties expected to be affected at first.
- Safety evaluations performed for the Votna 2 slab dam revealed a need for strengthening of the slab. A new bearing concrete slab was therefore constructed in 2006.
- Preliminary safety evaluations performed for the Votna 1 arch dam show that a satisfactory capacity of the arch will be maintained for at least 20 years from now. The evaluations of the arch pillar are, however, not yet finished and further FEM analysis will be performed.

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TABLE 1: Number of laboratory analyses performed according to each of the test methods.

Type of analysis	*Number of analyses*
Degree of capillary saturation (DCS) and concrete porosity	28
Dynamic E-modulus	54
Static E-modulus	12
Compressive strength	42
Splitting tensile strength	30
Analysis of plane polished sections	26
Analysis of thin sections	13

TABLE 2: Results from the laboratory examinations of the drilled concrete cores.

Dam – structure part	*Location*	*DCS [2] (%)*	*Crack Index [2]*	*Compressive Strength [2] (MPa)*	*Splitting tensile strength [2] (MPa)*	*Static E-modulus (E_C) [2] (GPa)*	*Dynamic E-modulus (E_{dyn}) [2] (GPa)*
Votna 1 – arch	Lower part	8/93/ 3	6/9/4	8/48.8/8.9	4/4.3/0.3	4/23.9/2.4	10/38.2/3.5
	Upper part	5/91/3	5/7/5	10/47.6/5.7	4/3.9/0.7	4/21.8/1.3	13/35.3/4.0
Votna 2 – pillar	Not sheltered	2/94/2	3/2/2	5/36.0/4.1	3/4.0/0.6	1/24.1/-	5/33.3/5.7
	Sheltered	5/87/2	3/1/0	10/39.4/2.9	8/4.1/0.4	1/26.6/-	9/37.6/4.1
Votna 2 – slab[1]	Lower part	3/93/1	3/6/4	3/42.1/1.2	2/3.9/0.4	1/23.2/-	4/39.5/0.7
	Middle part	3/95/3	3/7/5	4/47.9/4.2	5/4.4/0.4	1/23.4/-	7/36.7/2.1
	Upper part	2/94/1	3/14/1	2/48.8/2.8	4/4.1/0.5	-	6/34.4/2.8

[1] Downstream face of the slab (behind the frost protecting wall).
[2] The first number represents the no. of specimens tested. The second number represents the mean value of the series and the third number represents the standard deviation.

TABLE 3: Correlation between the FEM analysis and the measured displacements of the bolts installed in the top of the Votna 1 dam. The following "loads" were applied in the FEM analysis: uniform expansion of concrete (ε) = 0.96 ‰; no linear expansion over the section.

Location	*Bolt 11*	*Bolt 12*	*Bolt 13*	*Bolt 14*	*Bolt 15*
Measured radial displacement (mm) 1980 – 2005	4	66	8	61	5
Calculated radial displacement (mm) for ε = 0.96 ‰	4	57	8	70	7

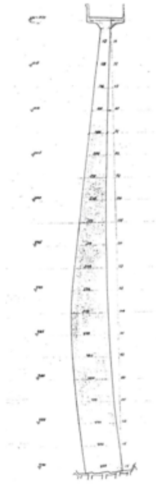

Figure 1: Cross-section of the arch dam (Votna 1). The maximum height is 55 m and the thickness increases from from 0.95 m in the top to 4.0 m in the bottom part.

Figure 2: Overview of the upstream face of the arch dam (Votna 1). On the nearest side there is a 17 m high arch pillar and a smaller slab concrete dam in the end of the arch.

Figure 3: Overview of the downstream face of the slab concrete dam (Votna 2). The circle shows the "problem corner" of the dam where the slab lifted from the supporting pillars.

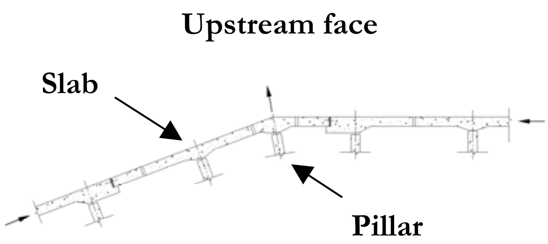

Figure 4: Sketch of "problem corner" on the Votna 2 dam (see Figure 3) where the front slab had been lifted away from the supporting pillars.

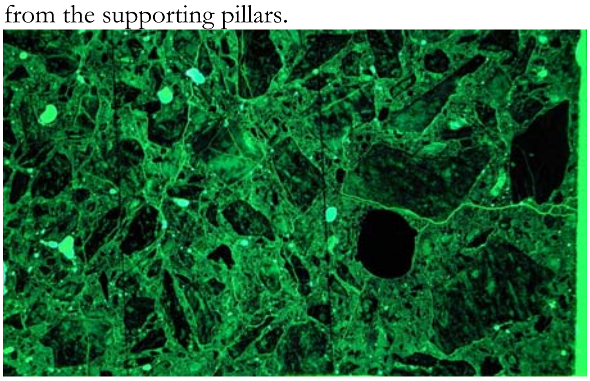

Figure 5: Photo of a plane polished section from the upper part of the slab in the Votna 2 dam (surface to the right). The measured Crack Index (CI) was 12.5. The photo covers an area of approx 100 x 150 mm².

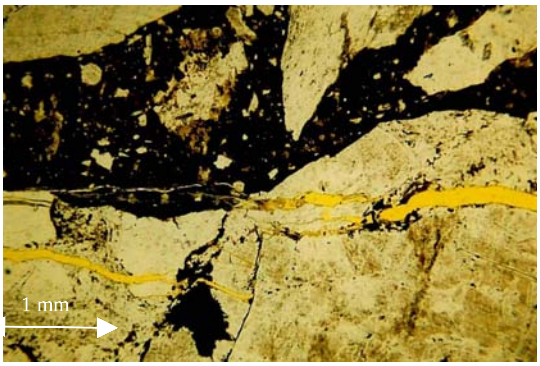

Figure 6: Photo of the thin section prepared from the core shown in Figure 6. Cracks into the aggregate and cracks from the aggregate into the cement paste filled with gel.

Figure 7: Votna 2. Photo of the new slab concreted upstream at the angular point (see Figure 3 and 4) as a preliminary measure. The arrows show the “water stop” used to seal the joints between the slab elements.

Figure 8: Votna 2. A drainage system was established by drilling several holes through the bottom part of the old slab (below the membrane).

Figure 9: Photo of the rehabilitated Votna 2 dam showing the new slab upstream.

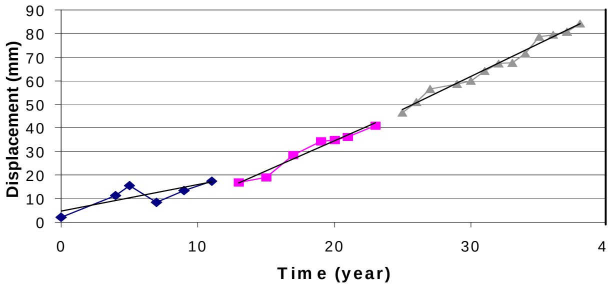

Figure 10: Votna 1. Yearly measured displacement of bolt 12 (in mm), from 1966-2004.

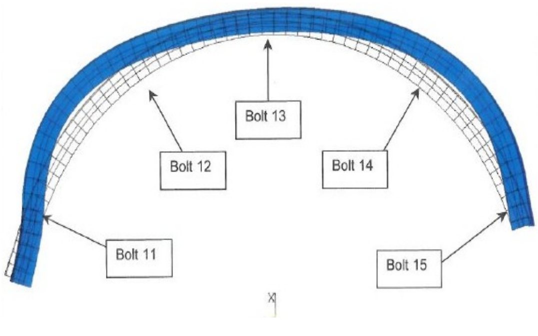

Figure 11: Votna 1. Location of the measureing bolts and the calculated horizontal deformations due to uniform temperature load.

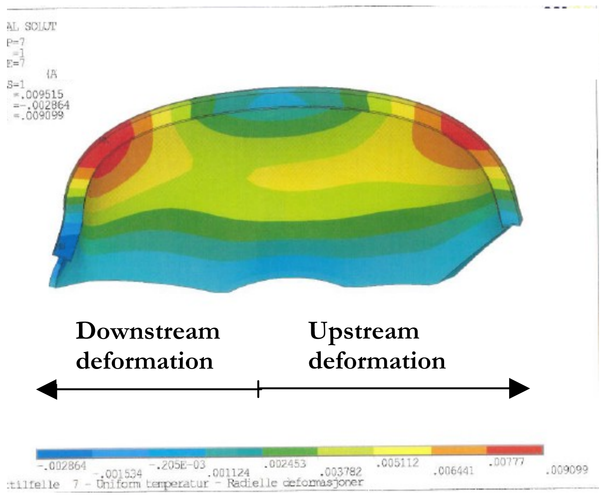

Figure 12: Votna 1. The calculated radial deformations due to uniform temperature load.