REVIEW OF METHODS USED AT HYDRO-QUÉBEC TO PREVENT ALKALI-AGGREGATE REACTIONS IN CONCRETE STRUCTURES

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ABSTRACT

The methods currently used at Hydro-Québec to prevent alkali-aggregate reactions (AAR) are generally derived from recommendations from the Canadian standards CSA A23.1 "Concrete Materials and Methods of Concrete Construction" and CSA A23.2 "Methods of Test for Concrete". These methods can be outlined as follows:

- Selection of non reactive aggregates (selective quarrying or aggregate beneficiation/dilution)
- Control of alkali content per cubic metre of concrete
- Use of mineral admixtures

This paper summarizes alkali-aggregate reactions and their background, as well as describing the methods of prevention used at Hydro-Québec. It also presents a case where silica fume has been used to prevent AAR in a new dam.
Keywords: Alkali-silica reaction, mineral admixtures, silica fume.

INTRODUCTION

Hydro-Québec is the largest energy producer in Québec operating on a territory of 1.5 km^2 and servicing 2,900,000 customers including 13,000 industrial accounts. It owns and operates more than 480 dams and 54 hydroelectric power plants, the most powerful being LG-2 with 5,328 MW. The total capacity is 30,434 MW and total energy produced per year is 142,778 GWh (1994).

By the year 2000 some 150 of Hydro-Québec's concrete dams will actually be at least 40 years old; about 100 of them will be 60 years old. The present condition of these structures reflects the effect of numerous factors that have brought on aging, premature or not. These factors include initial shrinkage causing latent microcracking, expansion and contraction tied to temperature cycles, larger infiltration entailing increased uplift, leaching and deposition of calcium salts that clog joints and drains, hydric swelling, freezing and thawing cycles, erosion, sulphatation, and alkali-aggregate reactions (AAR) (H.Q. 1993).

While the present condition of a dam often reflects a combination of several of these factors, deterioration caused by swelling due strictly to AAR may be critical. The well-known case of the Beauharnois hydroelectric development is a prime example of significant swelling due to AAR (Albert and Raphaël. 1987 and H.Q. 1992). Unfortunately, the Beauharnois structure is not Hydro-Québec's only dam where AAR has been discovered. Bérard and Roux (1986) name more than 20 dams where products of AAR are in evidence. A more recent study reports some 30% of Hydro-Québec's concrete dams are affected by AAR and 6% show no sign of reactivity. Because their condition is judged satisfactory, the remaining 64% have not been investigated in any great detail.

As these statistics may cause concern, it must be emphasized that not one concrete structure anywhere in the world has collapsed because of AAR alone[1] although, a few have been demolished by way of prevention (Hobbs. 1988). There are, however, several cases of Hydro-Québec concrete structures that have undergone work to thwart the effects of concrete swelling due to AAR or other factors. In some cases this has meant major rehabilitation to remove part of the old concrete and apply a layer of new concrete. This paper outlines the background of the AAR phenomenon and provides an overview of the preventive measures currently used at Hydro-Québec.

ALKALI-AGGREGATE REACTIONS

Description

Concrete consists for the most part of Portland cement, aggregates (stone and sand) and water. In hardened concrete, the hardened cement paste contains voids that are filled to some extent with a very basic alkaline liquid known as pore solution. Some mineral phases are chemically unstable in the presence of this solution and, when given conditions prevail, react to form products that occupy more space than the original phases. This results in concrete swelling, the phenomenon is known as alkali-aggregate reaction (AAR).

The details of the chemical reaction are well covered in the literature. The three following conditions are essential for AAR to occur:

- The aggregate must be alkali-reactive.
- Concrete made with reactive aggregates must have a minimum alkali content.
- The concrete must be exposed to an average relative humidity exceeding 75%.

When these three conditions are satisfied, an alkali-aggregate reaction occurs after a certain period of time. While it is generally more than five years before cracking sets in, the AAR may continue over several decades once it has started.

Alkali-silica reaction - Background

The first discoveries regarding the alkali reactivity of certain mineral components go back as far as 1916, when E.A. Stephenson, a geologist, reported that the reaction between feldspar and sodium carbonate produces a heavy gelatinous precipitate gel (Meissner. 1941). In 1923, J.C. Pearson and G.F. Loughlin, aggregate researchers, identified "dangerous aggregates" with regard to the performance of concrete (Blanks. 1941). In 1935, Professor R.J. Holden, F.M. Lea and C.H. Desch provided an initial understanding of how gels form in the alkali-aggregate interaction process (Leps. 1995). A little later, the American T.E. Stanton (1940), a materials and research engineer, California Division of Highways, observed concrete swelling and cracking in Parker dam (California) and attributed them to chemical reactivity of the aggregates. Since then, several American dams have been reported to be affected by AAR (Parker, Stewart Mountain, Gene Wash, Copper Basin, Buck, American Falls, Coolidge, Owyhee, Hiwassee, Chickamauga and Fontana dams) (Leps. 1995). In Canada, it was not until 1953 that E.G. Swenson identified the first case of AAR, in the concrete of a Montréal bridge (Grattan-Bellew. 1992). Cases of structures damaged by alkali-silica reaction have since been reported practically wherever concrete is

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1. There is nevertheless a California pipeline that collapsed because of AAR. (Haavik and Mielenz 1991)

used. The physicochemical mechanisms that enter into these reactions have been extensively investigated, and much progress has been made in elucidating these phenomena.

The alkali-silica reaction is the only type of AAR to occur in Québec, although with a wide variety of rocks belonging to three major geological families are present in the province -- Appalachians, St. Lawrence Lowlands and Precambrian. The Precambrian Shield north of the St. Lawrence Lowlands includes granitoid rocks containing fairly deformed quartz of igneous or metamorphic origin. This family of rocks usually exhibits a slow/late-expanding reaction characteristic of the sub-category of slow or late-expanding alkali-silica/silicate reaction.

PREVENTION AND REPAIR METHODS USED TO INHIBIT AAR

Methods to prevent AAR

In the past, Hydro-Québec technical specifications did not all prescribe special measures for dealing with AAR, but over the last ten years this has become common practice for hydraulic structures (Pedneault et al. 1992). In the case of small-scale projects involving small structures such as insulator foundations, however, it is not always possible to obtain certification of the aggregates from the concrete suppliers, which means that only sometimes were engineers able to choose suppliers who are using aggregates known to be nonreactive. Engineers can now refer to a list of quarries classified in terms of alkali reactivity by the Québec Transportation Ministry (Tremblay and Vézina. 1993).

The most recent specifications by Hydro-Québec refer to Canadian standards CSA A23.1 "Concrete Materials and Methods of Concrete Construction" and CSA A23.2 "Methods of Test for Concrete" to prevent AAR in concrete.

The proposed approach consists first in evaluating the aggregate in light of available data under real conditions similar to those to which the concrete will be exposed. In the absence of valid field experience with structures ten years old or more or if the aggregate has already shown potential alkali reactivity, the aggregate is rejected or laboratory tests are required. These are mainly expansion tests that produce results within a time ranging from a few days to one year or even two years in some cases.

If the test results point to potential reactivity, the aggregate must be rejected for use in Portland cement concrete. There are three main alternatives:

- Selective quarrying or aggregate beneficiation (dilution).
- Control of alkali concrete per cubic metre of concrete.
- Use of mineral admixtures.

Selective quarrying or aggregate beneficiation

Where possible, dilution of reactive aggregates with nonreactive aggregates in the quarry or selective quarrying of areas of nonreactive rock are methods often used to prevent AAR.

Hydro-Québec's most recent technical specifications usually stipulate aggregates used for concrete must conform to CSA A23, which sets out procedures for selecting concrete aggregates to inhibit AAR. The specifications sometimes go further than the standards, prohibiting use of certain types of aggregates that have exhibited alkali reactivity in Hydro-Québec structures located in the same region as the source of those aggregates (Chouinard. 1993). There is also SEBJ's[2] standard technical specification AA-80N-001 93, which makes mention of Appendix B of CSA A23.1, which states

2 SEBJ is a Hydro-Québec subsidiary (Société d'Énergie de la Baie James).

aggregates from each source must be checked for alkali-aggregate reactivity and each aggregate source must be approved by SEBJ.

Control of alkali content per cubic metre of concrete

One recommended means of inhibiting AAR when using reactive aggregates is to control the alkali content of the mixtures, given that there is typically little or no expansion below a certain alkali content in concrete mixtures containing reactive aggregates.

The use of low-alkali cements reduces the alkali content of concrete mixtures. Technically, a low alkali cement has a content less than 0.6% Na_2O equiv. (Na_2O equiv. = Na_2O + 0.658 K_2O). This is the total alkali content of the cement (ASTM C 114-85, atomic absorption or flame spectrophotometry).

SEBJ recommended the use of low-alkali cements for the structure of the James Bay megaproject. Starting in Phase 1, completed in 1982, the maximum alkali content prescribed in the technical specifications was 0.80% Na_2O equiv. For Phase 2 (1982-1996), this was reduced to a maximum of 0.70% and an average below 0.65%. The decision was aimed at preventing any risk whatever of alkali reactivity of the rocks used at James Bay. The rocks in question were granitoids containing fairly deformed quartz and similar to those classed as slightly reactive in some old dams (Rapides Farmers and Chelsea).

The new 1994 version CSA A23.1 (Appendix B) recommends a 3.0 kg/m^3 limit as a means of preventing AAR. Caution will be urged regarding mass concrete since problems have already occurred with alkali contents as low as 2.0 kg/m^3. The same is true for highly reactive aggregates or structures exposed to external sources of alkali, such as de-icing salt or sea water.

Most concretes poured thus far at James Bay probably have alkali contents below this 3.0 kg/m^3 limit, that is to say, about 2.5 kg/m^3. Evidently, simply limiting the alkali content of cement was sufficient to control the alkali reactivity of the aggregates used at James Bay, since no case of reactivity has been identified to date[3] (Verville. 1993).

Use of mineral admixtures

CSA A23.1-M90 states that silica fumes, fly ash, ground granulated blast-furnace slag and pozzolan used in sufficient quantities can prevent or reduce swelling due to alkali-silica reaction or the slow/late expansion such reactions produce. The new 1994 version of this standard is more explicit, mentioning several Canadian structures where mineral admixtures have been used to limit expansion due to AAR. One example is the Lower Notch dam in Northern Ontario, built with a reactive argillite (Sturrup et al. 1983) and 20% fly ash. No deleterious expansion has been observed after some 20 years (Hooton. 1990). In Britain, some dams built more than 50 years ago with reactive aggregates and fly ash are still in excellent condition (Thomas. 1992).

Here .again, the standard advises caution, particularly about tests to evaluate the effectiveness of mineral admixtures. It mentions that no test is needed if the concrete to be used contains less than 3.0 kg/m^3 alkalies and, further, that no additive is effective against alkali-carbonate reaction.

Hydro-Québec for the first time used at Témiscouata dam a mineral admixture to specifically inhibit alkali reactivity in a hydraulic structure. More specifically, this dam,

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3. The oldest structures at James Bay are about 18 years old.

rebuilt in 1993-1994, probably marks the utility's first utilization of condensed silica fume to inhibit aggregate reactivity. The case history of this dam is presented in the next section.

SEBJs technical specifications state use of silica fumes, pozzolan and calcium carbonates is prohibited, except as authorized in writing by SEBJ. As mentioned earlier, the preferred approach at James Bay was systematic selection of aggregates and use of low-alkali cements (Verville. 1993).

Témiscouata dam (Blanchette, Massad and Nadon 1992)

The Témiscouata dam was built in 1933 near Dégelis in Témiscouata, about 70 km southeast of Rivière-du-Loup. It includes a 188-m spillway equipped with 24 gates and a 153-m earthfill dam on the right bank, for a total length of 341 m. This structure regulates the flow of Madawaska River, a tributary of Saint-Jean River, which in turn supplies several power stations in New Brunswick.

The coarse and fine aggregates in the concrete of this development are of natural origin and consist of sedimentary rock, including pelites, greywackes and sandstone rich in quartz. Both grades of aggregates exhibit alkali reactivity resulting in slow concrete swelling followed by polygonal microcracking. Cracks are more extensive in emerged areas, such as the top of the piers and the deck. The downstream apron is also affected, albeit to a lesser extent.

In the 1960s concrete swelling caused all the piers to move in the direction of the earthfill dam, with the right end of that structure resting against the rock. The total displacement observed at the last pier on the fill side was about 225 mm. The possibility of rebuilding the dam was contemplated at that time. In the final analysis, the service life of the structure was extended by creating joints sealed with two asphalt boards installed every two piers (Munger. 1993). Most of these joints are now partly closed, resulting in extrusion of the bituminous sealer.

A subsequent measure consisted in recasting all of the pier and deck concrete (end of 70s, beginning of 80s). Fine polygonal cracking is now showing in this concrete. After a general review completed in 1993, it was decided to rebuild the Témiscouata development in 1993-1994 (phases 1 and 2).

To prevent AAR-related problems, the choice of aggregates for the new concrete was based on the practices recommended by CSA A23.1. The two local gravel pits were subjected to petrographic analyses, accelerated mortar and concrete prism expansion tests (South African and modified South African tests), concrete prism expansion tests at 38°C and modified chemical test ASTM C289. These tests revealed the potential alkali reactivity of the two aggregates and the sand. The option of using fly ash referred to in CSA A23.1 was considered, then dropped for technical reasons. The final choice involved using the lithic gravel deemed least reactive, together with cement with condensed silica fume (CSF) and a nonreactive sand from the Québec City area. This choice was based on results of accelerated expansion tests on concrete prisms placed in NaOH 1N at 80°C. These tests were conducted for various combinations of sand-aggregate-CSF cement (modified South African test) (Blanchette. 1989).

SUMMARY AND CONCLUSION

The methods used by Hydro-Québec to prevent AAR are in line with the main recommendations of Canadian standards CSA A23.1 "Concrete Materials and Methods of Concrete Construction" (Clause 5.5 and Appendix B) and CSA A23.2 "Methods of Test for Concrete," namely:

- Selection of nonreactive aggregates (selective quarrying or aggregate beneficiation/dilution).
- Control of alkali content per cubic metre of concrete.
- Use of mineral admixtures.

Over the past ten years Hydro-Québec has consistently tightened its technical specifications for the selection of concrete aggregates, at least for its larger structures (Chouinard. 1993). There is some room for improvement as regards smaller structures, e.g., concrete requirements for insulator foundations in distribution substations have not always taken account of the AAR factor, until recently in any case.

The list of Québec quarries classed by alkali reactivity (Tremblay and Vézina. 1993) would greatly help Hydro-Québec's engineers, specialists and technicians in selecting concrete aggregates.

In addition to selection of nonreactive aggregates and use of low-alkali cement, Hydro-Québec has used a mineral admixture to counter AAR at the Témiscouata dam rebuilt in 1993-1994. This was the first time Hydro-Québec used condensed silica fume to prevent AAR in a water-resources facility where selected aggregates have a slight potential alkali reactivity. The concrete behavior is monitored by Hydro-Québec by conducting expansion laboratory tests to validate this choice and correlate laboratory testing and structure behavior.

Mineral admixtures are not permitted for James Bay structures, unless specifically authorized by SEBJ. The preferred approach is selection of nonreactive aggregates and use of cements with an average alkali content of 0.65%.

Based on a general impression gained through conversations with Hydro-Québec engineers, not many measures have specifically addressed AAR to date, except perhaps for the Beauharnois dam and few other dams. In coming years, however, Hydro-Québec will carry out several major rehabilitation projects on its structures, making it essential for those in charge to use the most recent guides and specifications to cope with the AAR problem. Concurrently, research should continue so as to:

- Further elucidate the mechanisms of AAR;
- Improve quantification of the effects of AAR on concrete structures, including mathematical modeling;
- Improve prevention and repair methods for structures affected by AAR.

As Québec's leading user of concrete, Hydro-Québec has to remain at the leading edge of concrete technology to incorporate breakthroughs, as they emerge, in as many of its structures as possible.

Over the past ten years, Hydro-Québec has consistently tightened its technical specifications for the selection of concrete aggregates, at least for larger structures. However, there is some room for improvement as regards smaller structures; concrete requirements for electrical apparatus foundations in distribution substations have not always taken AARs and their effects into account, until recently in any case. The 1994 edition of Hydro-Québec standard SN 30.2 "Fourniture et mise en oeuvre du béton" contains specific sections which are either new or updated to reflect recent development in the field of AAR.

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