Alkali-Silica Reactivity in the Beauharnois Powerhouses, Beauharnois

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ABSTRACT

The Beauharnois power development is located on the St. Lawrence River near Lake St-Louis some 50 km upstream from Montreal. The powerhouses, which were built in three stages, are encased between two concrete wingwalls located on the right and left abutments. These wingwalls extend from the dikes to the intake and complete the reservoir closure (Figure 1). A study carried out in 1983-1984 concluded that alkali-silica reactivity is the principal cause for the abnormal behavior of the concrete observed at Beauharnois and proposed remedial measures.

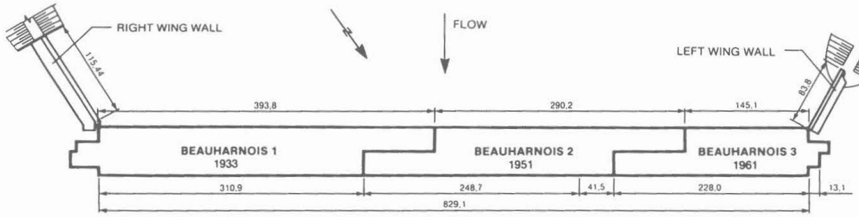

FIGURE 1 GENERAL ARRANGEMENT - BEAUHARNOIS

1. EXTENT OF THE PROBLEM

Seven (7) years after the construction of the Beauharnois 1 powerhouse, signs of undue deformations and concrete disaggregation became apparent. In 1970 an instrumentation network was implemented and since then regular inspections made it possible to follow the progress of the deformations and detect abnormalities, in particular the following:

. important residual deformations in the longitudinal direction of the intakes;

. the ovalness of the end units of powerhouses 1 and 3;

. the development of structural cracks at the junction of the water intakes and the concrete wingwalls;

. the deterioration of concrete works exposed to weathering or conditions of relatively high humidity.

2. PROBABLE CAUSES

The type of disorders observed led us to suspect the following causes:

- inadequacy of the original design;
- foundation instability;
- materials of a doubtfull quality.

Based on existing records of measured deformations and related calculations the first two causes were eliminated. Materials became the prime target. Untreated river water used in the concrete mixes, according to analyses, was found to be suitable, whereas the aggregates, which in all cases came from the Beauharnois rock formations (Potsdam sandstone), were found to be very reactive, as evidenced by petrographic analyses carried out in 1977. No cement characteristics were found available in existing records. However records of contemporary cement manufacturers lead us to surmise that the cements used during the construction period had about a 1% alkali content. The combination of that aggregate with cement of that period indicates a high potential for aggregate alkali reactivity.

3. CONCRETE STUDIES

PAST RECORDS

The main concrete characteristics of Beauharnois 1 and 3 were summarized using existing data. No records were found of the Beauharnois 2 concrete. However, because of many similarities existing between the first two powerhouses, it was assumed that concrete used for these powerhouses had the same characteristics

Characteristics	Beauharnois 1 and 2	Beauharnois 3
Specified strength	20,7 MPa	20,7 MPa
Cement content	377 kg/m^3	237 kg/m^3
Air content	----	4% ± 1%
Admixture	----	Pozzolith

RECENT ANALYSES

Physical Analysis

Physical tests were carried out to determine the air content, permeability, compressive strength, Poisson's ratio, modulus of elasticity, adsorption, saturation and volumetric changes. The test results indicated on the one hand that the Beauharnois 1 and 2 concrete has a deficient air entrainment system and on the other hand, that the modulus of elasticity of all three powerhouses showed a decrease of about 30% over the years. All other tests gave normal results.

Chemical Tests

a) Petrographic Analyses

These analyses confirmed that the reactive component of the Potsdam sandstone aggregate is a chalcedonic form of silica which cements together individual, non-reactive quartz grains. Even though both the coarse and the fine aggregates were made of the same sandstone formation, only the coarse aggregates produce an expansive reaction. The fine aggregate reaction produces a non-expansive product relatively high in calcium.

b) Expansion Rate Determination

In 1982, concrete expansion measurements were carried out on concrete core samples taken from all three Beauharnois powerhouses. Measurements taken on samples submerged in water made it possible to evaluate the annual rate of concrete expansion for each powerhouse. The average annual rates that were determined are as follows:

Beauharnois 1	0,006%
Beauharnois 2	0,005%
Beauharnois 3	0,005%

c) Determination of Potential for Further Expansion

The potential for expansive alkali-silica reactivity was evaluated by measuring the rate of expansion on two groups of concrete samples obtained from all three powerhouses. The first group was immersed in water and the other in a NaOH solution. The difference in expansion rate of these two groups is due only to alkali-silica reactivity. The results indicate that concrete from all three powerhouses have a potential for further expansive reaction (Figure 2).

d) Effect of Temperature and Alkali Content on Expansion

In order to verify certain parameters, expansion measurements were made on concrete prisms and mortar bars which were recently fabricated using sand and coarse aggregates obtained by crushing rock cores of Potsdam sandstone taken from the powerhouse foundations. Samples for testing were prepared using cement with an alkali content varying between 0,40% and 1,15%.

The expansion measurements made on concrete prisms revealed that the reaction is expansive if the alkali content is in the order of 0,90% or more and that the expansion rate is about twice as much if the ambient temperature is 22,8^{0}C rather than 4,4^{0}C. No expansion of any significance was noted on the mortar bars.

e) Osmotic Cells

In order to further characterize the expansion potential for further alkali-silica reactivity in Beauharnois concrete, tests using osmotic cells were carried out on coarse aggregate samples taken from concrete cores. A typical flow rate variation is given on Figure 3.

Test results confirm that concrete of all three powerhouses contain both particles capable of expansion and non-expansive particles.

f) Relative Humidity Determination

In order to evaluate the amount of relative humidity contained in the concrete, 72 samples were taken in different places both inside and outside the powerhouses and at different depths in the concrete. The results showed that relative humidity increases rapidly with depth. The depth at which the level of 85% relative humidity is attained depends on the degree of concrete exposure to humidity. Tests revealed that this depth varied between 75 mm and 350 mm below the concrete surface. These tests confirmed that the concrete of all structures contains a sufficient amount of water for alkali-silica reactivity.

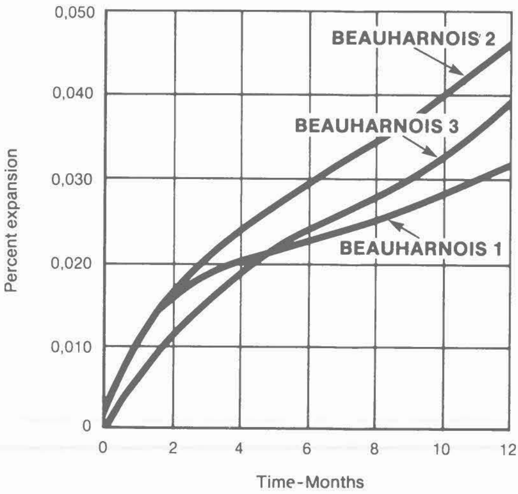

FIGURE 2 AVERAGE RATES OF EXPANSION ON CONCRETE CORES IMMERGED IN A NaOH SOLUTION

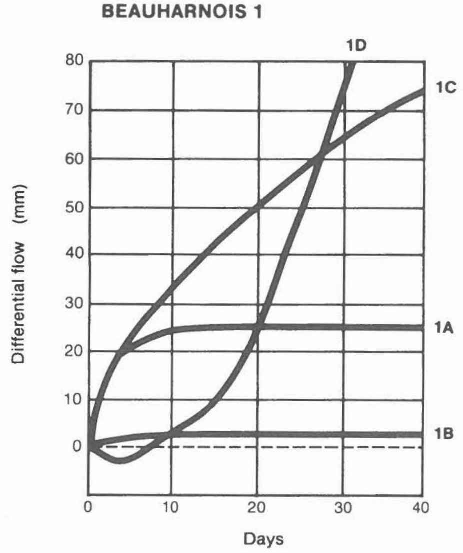

FIGURE 3 RESULTS OF OSMOTIC CELL TESTS FOR AGGREGATE PARTICLES

4. STRUCTURAL STATE OF THE WORKS

Calculations are based on deformation measurements taken on the structures, and also on the concrete properties, as determined from laboratory tests.

Stress calculations were based on the STRESS 11 computer program; all structures were simulated as two-dimension rigid frames, except for the Beauharnois 3 stayring which was simulated as a rigid three-dimension frame. Concrete expansion was simulated as an increase in temperature for all members; this calculation artifice was used by analogy to simulate the effect of concrete expansion assuming that the reaction will produce an elongation in members proportional to their length, similar to the elongation caused by a rise in temperature.

As an example, the structural model of the intakes used to calculate the increase in stresses due to elongation of the intake is shown in Figure 4, which also gives the calculation results.

The structural study confirmed that the overall stability of the structures was assured and that their resistance in their present state has not been unduly affected by the alkali-silica reactivity. However, the interaction of the wingwalls and the intakes at both ends of the powerhouses due to concrete expansion of both structures produces detrimental stress concentrations.

Increases in stress in the water intake piers caused by the lengthening of the structure

Present condition, before separating the left wing wall from the intake

	Stresses (MPa) Compression or tension			Stresses (MPa) Compression or tension	
Unit	Central pier	Lateral pier	Unit	Central pier	Lateral pier
AB	9,38 *	15,55 *	20	0,03	0,01
1	14,84 *	10,23 *	21	0,00	0,00
2	6,66 *	4,59 *	22	0,02	0,01
3	7,97 *	5,50 *	23	0,04	0,03
4	3,97 *	2,74 *	24	0,07	0,04
5	4,33 *	2,99 *	25	0,10	0,08
6	2,34 *	1,61	26	0,14	0,09
7	2,37 *	1,63	D1	0,20	0,14
8	1,38	0,95	D2	0,24	0,17
9	1,31	0,90	27	0,36	0,25
10	0,80	0,55	28	0,43	0,29
11	0,72	0,50	29	0,65	0,45
12	0,46	0,32	30	0,74	0,51
13	0,41	0,28	31	1,17	0,81
14	0,27	0,19	32	1,28	0,88
15	0,22	0,15	33	2,12 *	1,46
16	0,15	0,10	34	2,18 *	1,50
17	0,12	0,08	35	3,83 *	2,63 *
18	0,08	0,06	36	3,71 *	2,56 *
19	0,06	0,03	37	4,49 *	7,45 *

These stresses are based on deformations obtained from measurements made between 1974 and 1982 on pendulums located at both ends of the intake.

* Cracked pier, tension stress is greater than its capacity at rupture.

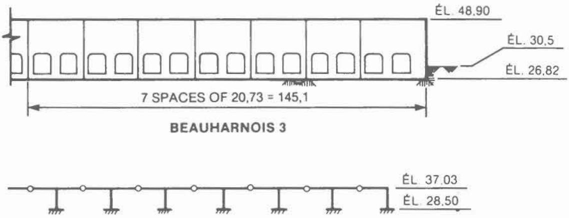

FIGURE 4 STRUCTURAL MODEL OF THE WATER INTAKES

5. CORRECTIVE MEASURES

The main corrective measure proposed consists of eliminating interaction between the water intakes and the wingwalls. The deformations resulting from the separation of these structures were predicted using:

- presently known rates of deformation;
- actual concrete properties as determined by recent tests;
- an anticipated total life span of 65 years for the duration of the reaction, taking into account the present age of the concrete which is still expanding after 50 years and similar cases found in technical articles.

The engineering design of this separation is presently under study. It is felt that this corrective measure is the first step to be taken in the overall solution of the problem.

6. CONCLUSIONS

a) Concrete expansion due to alkali-silica reaction is the main cause of the abnormal behavior of the structures.

b) The life span of the reaction exceeds 50 years.

c) The deformations at the junction of the wingwalls and water intakes may be detrimental.

d) The overall stability of the structures is consistent with USBR standards.

e) The complexity of the problem due to the alkali-silica reactivity denotes the importance of making a global analysis at first to identify the causes and effects, and then to formulate the corresponding corrective measures.

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