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THE ST. LAWRENCE SEAWAY (QUÉBEC, CANADA): A CASE STUDY IN THE MANAGEMENT OF STRUCTURES AFFECTED BY ALKALI-AGGREGATE REACTION

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ABSTRACT

This paper aims to present the issues relating to the diagnosis, the monitoring and the rehabilitation strategy developed to deal with the AAR affecting the locks of the St. Lawrence Seaway located between the Port of Montréal and Lake St-François.

The most evident manifestations of the AAR in the locks of the St. Lawrence Seaway were first identified in the mid-70's, approximately 20 years after construction. Misalignment of gate leafs and of Taintor Valve lever arms led to operational problems which required immediate remedial work, and the development of an intervention strategy to deal with the ongoing expansion in the future.

Assessment of AAR damage through detailed inspections and testing led to the implementation of a comprehensive monitoring program which includes inverted pendulums, extensometers, crack width measurements and monolith displacement surveys. Results were incorporated into a finite element expansion model to determine the extent of possible damages in the future.

A remedial repair program was instigated based on the results of the monitoring and finite element modelling. Current repairs include partial removing and reconstruction of concrete recesses for movable components such as stop logs, gates and Taintor Valves, crack injection with polyurethanes and/or cement grouts, and external confinement of components such as piers and counterweights. Possible rehabilitation options being considered include stress relaxation techniques, post-tensioned anchors, and wall resurfacing.

Keywords: Alkali-aggregate reactions, condition assessment, monitoring, modelling, rehabilitation.

INTRODUCTION

The navigation locks of the St. Lawrence Seaway are typically exposed to various aggressions which affect concrete durability. To cite a few: freezing and thawing cycles, watering/de-watering cycles, thermal effects, hydro-mechanical effects, steel reinforcement corrosion, and ship impact. Among these factors, we must now add the alkali-aggregate reaction (AAR) which is becoming of prime importance. In the case of four of the locks located in the Eastern Region of the St. Lawrence Seaway, excessive swelling of the concrete due to AAR has caused operational and structural problems of such magnitude that expensive remedial actions are required on an annual basis. Up until 1999, it has been estimated that approximately 2,500,000CDN$ had been spent on machine realignment and concrete repairs which were directly attributable to AAR.

DESCRIPTION OF THE STRUCTURES

The St. Lawrence Seaway locks in the Eastern Region were built between 1956 and 1959. They are made of gravity type retaining structures of varying lengths (from 12.2 m to 34.1 m long), called monoliths, adjoining one another to form continuous walls. The aqueducts, cable galleries, machine rooms, valve and gate recesses, and all other operational components are incorporated into the structure of each monolith. The dimensions of a typical lock (Fig. 1) are 24.4 m wide and vary between 1173.5 m and 2036 m long, including the lock chamber (approximately 460 m long) and the upstream and downstream approach walls.

The four locks under consideration in this paper are located in St-Lambert (Lock 1), Côte St-Catherine (Lock 2), and Beauharnois (Locks 3 and 4), in Québec, Canada.

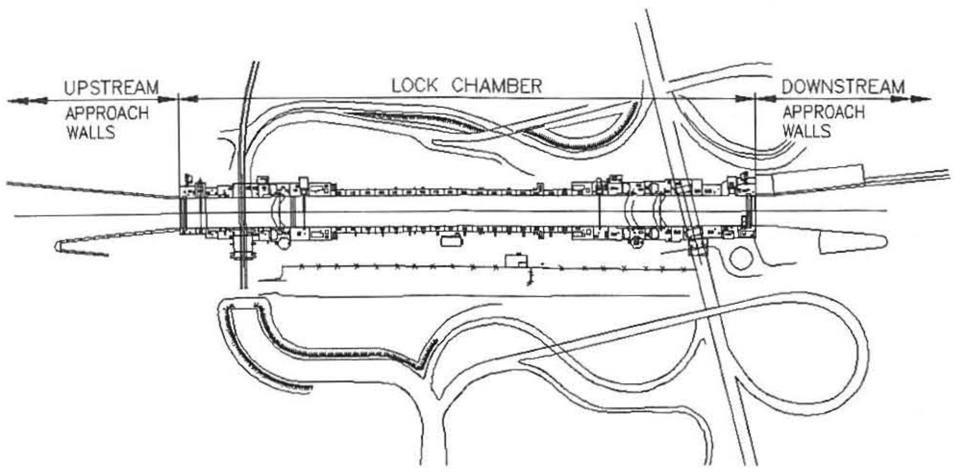

Fig.1: Typical lock: Plan view

DIAGNOSIS AND EVALUATION

The St. Lawrence Seaway has been documenting a variety of problems over the years at each of the four locks under consideration, with records dating back to the early 60's. These problems include the squeezing of stop log guides and ice gates, pipe and shaft misalignments, jamming of valve seals, cracking within the cable galleries and the general deterioration of the coping concrete. Identification of AAR as the single most significant cause of distress was determined in the mid 70's through the following process:

- Analysis of the various displacement records and the establishment of specific trends;
- Visual inspections of the surface cracking compared to crack patterns consistent with the effects of AAR;
- Results of laboratory testing to determine the type of aggregate, the presence of the reaction gel, the characteristics of the concrete and the reactivity potential.

Having clearly established AAR as the main source of the problems, the evaluation of the risks involved and the extent of damages to be expected was accomplished by answering the following questions:

- Did the observed damages compromise the integrity, stability or serviceability of the lock structures?
- Can the observed damages accelerate or otherwise affect other deterioration mechanisms currently at play, such as frost action, de-watering cycles, corrosion or other?
- What is the residual life of the reaction, at what rate, and what will be the worst deterioration scenario once the reaction has exhausted itself?

These questions drove the monitoring and modelling programs to follow, which in turn dictated the intervention strategy developed by the St. Lawrence Seaway to deal with the AAR affected locks.

CONCRETE INSPECTION AND TESTING

Visual Inspections

Surface map cracking, characteristic of AAR, was noted in various stages of development in all locations at all four locks. Further evidence could be seen at the vertical joints between monoliths, most of which show signs of significant compression due to concrete expansion.

Cracking has also been observed in the cable galleries at all four locks. These cracks can be grouped into three major types:

- Large angled shear cracks due to relative movements within a monolith, particularly in areas of stress concentrators such as abrupt changes in geometry, openings, etc.;
- Continuous horizontal cracks at the construction joint near the roof level of the galleries due to the rotation of the monolith toward the lock;
- Closing of vertical construction joints.

Concrete Aggregates

At both Beauharnois Locks, the coarse aggregate was taken from the Postdam Sandstone Formation from which the locks were excavated. This fine-grained, grey-white quartzitic sandstone is well known as being alkali-reactive, with a long record of reactivity having been documented at the nearby Beauharnois power plant (Albert and Raphaël 1987). At the St-Lambert and Côte St-Catherine Locks, the coarse aggregate is a mixture of 90% argillaceous and crystalline dark grey limestone and 10% diabase. Although not as well known as for the Postdam sandstone, the reactivity of these rocks has been noted by a few researchers (Fournier and Bérubé 1991, Bérard and Roux 1986).

Content of Soluble Alkalis and Concrete Characteristics

Cores were taken from each lock and tested for water soluble alkalis in 1996 at Laval University using the method recommended by the Ministry of Transportation of Ontario (Rogers and Hooton 1993) and modified by Bérubé et al. (2000). Another series of cores were taken in 1999 to test for concrete mechanical properties. The average results obtained at each lock are shown in Table 1.

TABLE 1: Properties of Concrete Cores

Lock	Na_2O_{eq}*	f'_c	E	μ	f'_t	Absorption	Expansion
St-Lambert	3.03 kg/m^3	33.2 MPa	18.7 Gpa	0.215	2.95 MPa	3.61%	8.83 ($10^{-6}/^oC$)
Côte Ste-Catherine	4.49 kg/m^3	36.3 MPa	21.0 Gpa	0.183	-	-	-
Beauharnois 3	3.75 kg/m^3	-	-	-	-	-	-
Beauharnois 4	4.84 kg/m^3	30.6 MPa	14.2 Gpa	0.243	-	-	-

*Water soluble alkali content

Another set of expansion testing was initiated in 1999 from cores taken at the St-Lambert Lock in March 1999. Partial results at 308 days yield 0.02% expansion at 100% relative humidity and 38°C, indicating a still active reaction.

The yearly rates obtained from the concrete cores can be extrapolated at 0.025%. Such a rate would translate into monolith displacements at gate locations in the order of 3 to 3.5 mm at each side, whereas measured values on site vary between 0.5 to 2.0 mm depending on the location. It is indeed difficult to extrapolate the expansion rates obtained in the laboratory onto the structures in service. It is normal to expect in-situ displacements to be less than laboratory predictions because of physical confinement, lower temperatures and humidity levels. The laboratory results are very useful to determine that the reaction is still in progress, and that it can probably continue at a similar rate. However, the actual rate of expansion of the concrete in each lock is best measured from in-situ monitoring.

MONITORING

Monitoring of different components of the locks has been going on for many years, with the longest continuous records dating back to 1967 (Table 2). Compilation and analysis of these records led to the conclusion that the St-Lambert Lock had the most numerous and reliable data showing a strong AAR reaction, and as it is representative of the other locks, more emphasis was given to that lock in developing the detailed monitoring program prepared in 1995. Monitoring records can be divided into two groups: prior to 1995 when records were mostly structure specific and executed as needed, and after 1995 which marked the initiation of a rigorous and comprehensive monitoring program (Table 2).

TABLE 2: Monitoring Records

Year started	Records started prior to 1995	Frequency
1967	Ice flushing gate dimensions	Annually
1986	Stop log slot dimensions	Annually
1987	Valve side seal dimensions	At every lock de-watering
1992	Upstream ship arrester	From 1992 to 1995
1992	Gate Drive alignments	Continuous, on a rotation basis
1994	Lock wall verticality	At every lock de-watering
1994	Concrete crack Inventory	At every lock de-watering
1995	Monolith displacement land surveys	Annually
Year started	**Records started after 1995**	**Frequency**
1996	2 Inverted pendulums at Lock 1	Twice/year
1996	2 Inclined extensometers at Lock 1	Twice/year
1996	42 Horizontal extensometers at Lock 1	Twice/year
1996	5 Crack width measurements at Lock 1	Twice/year
1997	2 Inverted pendulums at Lock 1	Twice/year
1997	2 Inclined extensometers at Lock 1	Twice/year
1998	2 Inverted pendulums at Locks 2 & 4	Twice/year
1998	4 Crack width Measurements at Lock 2	Twice/year
1999	2 Inverted pendulums at Locks 2 & 3	Twice/year
1999	8 Crack width measurements at Locks 3 & 4	Twice/year
(2000)	2 Inverted pendulums at Locks 3 & 4	Twice/year

The land surveys for the alignment and elevations of all the monoliths for each lock have been modified to be compatible with the new network of 73 monitoring instruments installed between 1995 and 2000. All elevations and displacements can now be linked to the inverted pendulums at each lock.

The inverted pendulums go through the entire depth of the monoliths and extend an average of 10 metres into the bedrock (Fig. 2). The pendulums were supplied by Hydro-Québec and installed both upstream and downstream of each lock, beginning with the St-Lambert Lock. Locations were chosen as close as possible if not within the monoliths housing the mitre gates. The pendulums are protected by small sheds built at the edge of the coping at each location.

The inclined extensometers (SAM model) were supplied by ROCTEST and installed in the St-Lambert Lock (Fig. 2). There are two extensometers in the north gallery, and two in the south. Each unit is inserted into a drilled hole at an angle varying between 27 and 30 degrees to the vertical, and extends 5 metres into the bedrock. The head of each extensometer terminates at the floor level of the Taintor Valve machine rooms. Temperature gages were installed at different rock and concrete elevations at each extensometer.

The horizontal extensometers are made of 6 mm diameter Invar strands inserted into PVC sheathing in sections of 25 meters long maximum (Fig. 2). In all, 20 sections were installed in the South Cable Gallery, and 22 in the North Cable Gallery at the St-Lambert Lock. Each horizontal extensometer is equipped with a reading dial and reference table, and is anchored at one end only to allow for measurements of longitudinal variations.

Crack measurement units as developed by Hydro-Québec (PATIR) provide displacement records of the cracks along all three axes. The units are installed so that one of the axes is perpendicular to the crack for direct reading of its opening and closing.

The first two years of results at the St-Lambert Lock demonstrated that all instruments perform well and provide information on the concrete displacements. Data from one type of instrument (extensometers) was validated by the other type (inverted pendulums), indicating a redundancy in monitoring. All other locks were subsequently equipped with inverted pendulums and crack measurement units only.

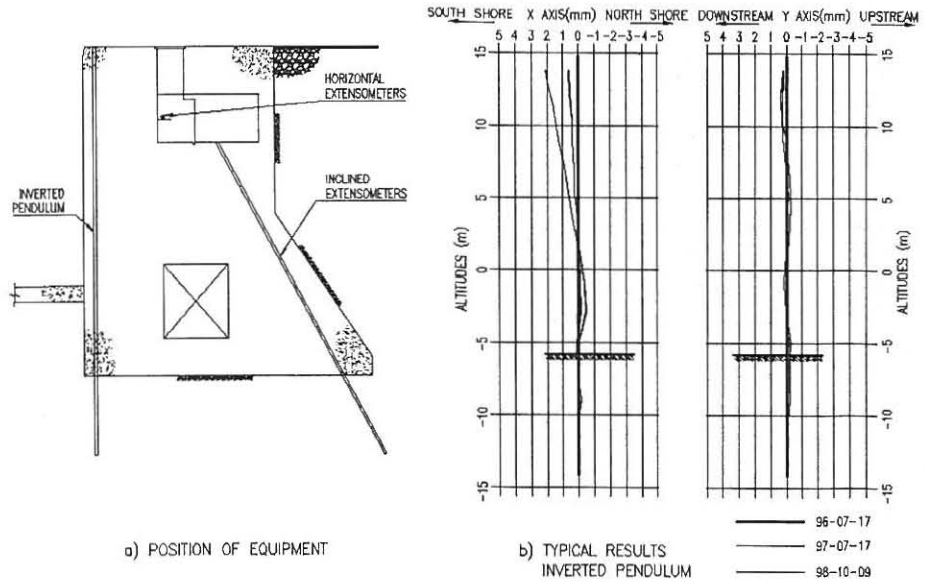

Fig. 2: Monitoring equipment for a typical monolith

MODELLING

The main objective of the numerical analysis was to assess the deformation trends and mechanical damage in local areas of the St-Lambert Lock (typical lock subjected to AAR), and to predict the long term implications of the on-going reaction in the future.

The finite element model was developed by Hydro-Québec as part of a mandate to study the effects of AAR at the St-Lambert Lock. Their model is based on the premise that the formation of silica gel will lead to progressive expansion in the concrete. The rate of expansion in the model is considered controlled by the alkali content, the level of confinement stresses, and the temperature and humidity of the concrete. The model also takes into consideration the effect of varying temperatures on the rate of the reaction and on the progressive deterioration of the mechanical properties of the concrete. The finite element model is designed by using in part the COSMOS/M (GEOSTAR) software for pre- and post-treatment, and in part the McFEM software developed by McMaster University for 3D modelling.

The Models

In the first phase of the project (1996-1998), the models developed incorporated the monoliths U4N to 23N as follows:

Model 1: Monoliths 1N to 18N.
Model 2: Monoliths U4N to 23N (model 1 plus additional monoliths both upstream and downstream).
Model 3: Monoliths U4 to 10, N & S (including the connecting transverse floor slab).
Model 4: Monoliths U4 to 10, N & S (same as model 3, but with a finer mesh).

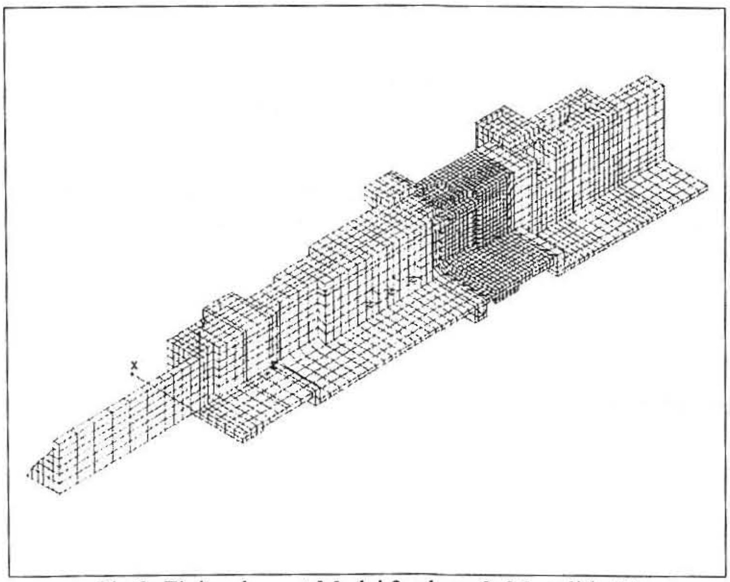

Fig.3: Finite element Model 3, phase 2: Monolith 7N

In the second phase of the project (1999-2000), refinement of the models concentrated on specific monoliths chosen for their operational importance (Fig. 3).

All finite elements are eight-node three-dimension solid elements. The bottom of the structure (the floor slab) is considered as a fixed boundary.

The Parameters

A certain number of assumptions for the mechanical properties of the concrete needed to be made at the beginning of the first phase of the project, while waiting for the results of the laboratory testing on the concrete cores taken at the St-Lambert Lock. These were:

E_o = 15 000.00 MPa (initial modulus of elasticity);
μ = 0.2 (Poisson's coefficient);
f'_c = 27 MPa (initial compressive strength);
f'_t = 2.7 MPa (initial tensile strength).

These values were adjusted in the second phase of the project to reflect the in-situ values obtained from the cores testing, with the appropriate corrections. It was seen that although essential parameters of the numerical analysis program, the mechanical properties do not have a great impact on the results.

The program is actually most sensitive to the temperature data and to the volumetric expansion parameter. For the analysis, the rate of expansion below 10°C was assumed to be negligible as the kinetics of the chemical reactions are slower at lower temperatures. The number of months per year with temperatures above 10°C was evaluated from in-situ records which determined that temperatures were above the threshold an average of 7.5 months/year. It was also assumed in the analysis that no significant expansion took place over the first ten years of service.

The expansion parameter used in the model was initially determined using the annual expansion rate of 0.0077%/year recorded at the nearby Beauharnois Power Plant. It will be adjusted in the final model to reflect the results from the expansion testing of the concrete cores taken at the St-Lambert Lock. Since the expansion parameter is affected by cement type and content, aggregates, water/cement ratio, and the humidity of the concrete, a sensitivity analysis was also performed in the first phase of the project in order to account for the variation of these factors.

The Results

Results of the sensitivity analysis on the volumetric expansion parameter performed in the first phase of the project are summarised in Table 3.

TABLE 3: Results of the Sensitivity Analysis

TEST	Expansion rate (%)	Closing distance between Monoliths 1N & 1S
1	.00385	8 mm
2	.0077	27 mm
3	.01155	53 mm
4	.0206	113 mm

The results of the analysis at the end of the first phase using an expansion rate of 0.0077% show that the predicted trend of expansion is logical and thus that its simulation is feasible. The models were modified slightly in the second phase to concentrate on monoliths 1 and 7 with a finer mesh to increase the reliability of the predicted future trends. These include the continued closing in of the lock walls, and also the propagation of a crack system from the inner top corner of the aqueducts through the monoliths and to the fill side, effectively separating the monoliths in two. Remedial measures were then designed to guard against this possible structural failure on the one hand, and to continuously offset the effect of the gradual closing in of the lock walls on the other hand.

REMEDIAL MEASURES

Concrete swelling and distortions have reached such proportions over the years that remedial measures are now being executed on a continuous basis as follows:

Mechanical adjustments -- Mitre gates horizontal sills and vertical contact blocks re-positioning and Taintor Valves lever arms re-alignment have been going on since the early 90's. Work includes the removal of mechanical parts and their refurbishing as required, the removal of the concrete, the installation of new anchor bolts and base plates to new positions, new concrete and new water seals. Typical cost per project is 250,000CDN$. Other mechanical components requiring re-alignment include sector gates, sluice gates, stop logs, ship arresters, etc. Total cost per lock is well over a million Canadian dollars and these interventions last from 10 to 20 years only. They are however necessary for reliable operational continuity of the locks.

Modification of concrete recesses -- Structural replacement of a lock structure is obviously impossible. Only parts of the structure can be replaced or modified. These include most concrete recesses for mechanical components which close across the lock. Work includes concrete removal, installation of guard and support rails to new positions, and concrete re-construction to provide additional room for future expansion. Typical costs per recess on both sides of the lock are 200,000CDN$. There are from six (6) to eight (8) such recesses per lock.

Grouting -- Crack injection is performed annually on a priority basis at each of the four locks. These measures are considered temporary as cracking will open up again after a certain time. However, water infiltrations through the cracks are unacceptable on an operational basis, putting at risk valuable mechanical and electrical components. Grouting costs an average of 250,000CDN$ per year, and the grouting program will continue to require this level of expenditure for at least the next 6 years.

Future rehabilitation measures -- The adopted measures to date were aimed at maintaining the operational continuity of the St. Lawrence Seaway and as such have been successful. These measures however address tolerances at specific locations only. Long term prevention of overall general trends established by the modelling must also be addressed, and will require a different type of intervention. Consideration is currently being given to the use of post-tensioned anchors across the major crack systems. Continued monitoring of the monolith displacements will also dictate the timing for entire wall resurfacing for which pre-fabricated concrete panels are currently being considered. External confinement of the counterweights of the vertical lift bridges at the St-Lambert Lock will likely be implemented in years 2001 and 2002.

CONCLUSION

Four of the locks of the St. Lawrence Seaway located in the Eastern Region between Montréal and Lake St-François are severely affected by AAR. The rate of swelling has been identified as high, and conclusions of the concrete testing at each lock are that the reaction will likely continue at similar rates for many more years.

Information gained from the monitoring compared to the theoretical simulations and from the post-mortem of the earlier remedial measures is very helpful. It is now evident that pro-active measures must be undertaken within the next decade to guard against potential structural failures on the one hand, but also that localised interventions must be planned on a continuous basis to provide operational continuity as the swelling process continues.

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