COMBINATION OF NUMERICAL MODELLING AND LABORATORY TESTING TO ASSESS THE ALKALI-SILICA REACTION (ASR) AT RAPIDES-DES-ÎLES HYDROELECTRIC POWER PLANT, QUÉBEC, CANADA

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Abstract

The hydroelectric power plant Rapides-des-Îles is located about 500 kilometers northeast of Montréal, Québec, Canada. The concrete of this 238 m long and 34 m high power plant is affected by alkali-silica reaction since its construction, which began in 1966 and ended in 1967.

At the beginning of the construction of RDI development, the laboratory testing had not demonstrated potential reactivity between aggregates and alkalies. The reaction and associated concrete swelling have caused functionality issues at the gates of the spillway, misalignments of the generating units that required several realignments over the years and induced some polygonal cracking in several places as well as structural cracks aligned parallel to main reinforcement. Consequently, various technical surveys have been done over time to diagnose and confirm the presence of an alkali-silica reaction associated with the coarse aggregate.

Since the degree of swelling associated with ASR measured at monitoring devices did not seem to slow down, a numerical modelling program was initiated in 2014 to evaluate the behavior of the main dam and to reproduce its past and future behavior. After studying different models, the numerical model developed by Electricité de France (EDF) - Code_Aster - was selected.

This numerical model requires the evaluation of several parameters characterizing the different phenomena: mechanics, creep, hydric and ASR effects. This assessment is made by conducting a series of laboratory tests from concrete cores extracted from the dam along with concrete cylinders made with the original aggregate to characterize the concrete from the beginning. This article presents the laboratory test program defined to determine the parameters specific to AAR in the model.

Keywords: AAR modelling, history case, dam, Code_Aster, laboratory tests.

1 INTRODUCTION

The Rapides-des-Îles hydroelectric power plant (thereafter RDI) is located about 500 kilometers northeast of Montréal, Québec, Canada. The concrete of this 238 m long and 34 m high power plant is affected by alkali-silica reaction since its construction, which began in 1966 and ended in 1967 with the commissioning of units 2, 3 and 4, followed by the one of the unit 1 in 1973. The development consists of a power plant equipped with four Francis turbines with a total power of 136 MW, a concrete main dam including an auxiliary spillway, a main spillway and four embankment dams. (See Figures 1 to 6)

Regarding data from the monitoring system for the main spillway, the downstream plant, the upstream and central points on piers of the auxiliary spillway, vertical displacement rates were respectively 0.90, 0.72, 1.07 and 1.00 mm/year. This corresponds to the respective deformation rate of 82, 45, 36 and 100 μm/m/year. These rates are similar or even higher than those measured at other Hydro-Québec dams also affected by AAR [1].

Like all mass concrete dams, the RDI development is particularly vulnerable to deleterious chemical reactions and related concrete swelling. The pre-existing favorable conditions are:

- high intrinsic level of humidity,
- high initial temperature resulting of hydration heat during the construction,
- low stress level,
- expected life of 50 years or more, and

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- fairly highly alkali-reactive coarse aggregate.

In addition, the initial cracking due to shrinkage and thermal gradients increases the volume of the connected porosity.

2 Previous work [2,3]

The issue of alkali reactivity potential of aggregate at RDI has been considered from the initial stages of its construction in 1964. The engineers in charge of assessing the aggregate qualification prescribed the standard test methods existing at that time to determine the alkali reactivity potential of aggregates. The first test was the mortar bar expansion test - ASTM C227-60[4] "Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method - 6 months)" while the second was the chemical - ASTM C289-63[5] "Standard test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method – 24 hours)".

Several sources of aggregates were subjected to this chemical reactivity and no one had shown the potential for alkali reactivity. The results on mortar bars made with the same coarse aggregates that were eventually selected for the RDI concrete showed expansions of 0.017% or lower either with high and low-alkali cement mixes, which is below the specified limit of 0.10% at 6 months by the ASTM C227 test.

The first investigations done on the problems of swelling and cracking at RDI began in 1974 [6]. The presence of an alkali-silica reaction was confirmed in petrographic examinations mentioning the presence of silica gel associated with the coarse aggregates [7,8,9,10]. Several other core sampling campaigns were held in the 2000s including residual expansion test with 150x300 mm cores stored at 38°C at 95% RH or in 1N NaOH [11,12,13].

Other accelerated mortar bar expansion tests were done with an "original" aggregate, e.g. from the RDI site and with similar characteristics to those of the true original coarse aggregate, this one had been produced from the rock excavated at the construction site. These tests made at 80°C in 1N NaOH all confirmed the alkali reactivity of coarse aggregate described as meta-greywacke and meta-siltstone (see Figures 7 to 13). Note that the sand fraction taken from a glacial deposit, rich in quartz and feldspars, is considered non-reactive.

Regarding the basic mechanical properties, the compressive strengths generally varied from 25 to 30 MPa with relatively low elastic modulus between 7 and 12 GPa, the latter confirming the usual effects of microcracking combined with silica gel deposition into those microcracks for concrete affected by a well-developed alkali-silica reaction. Nothing abnormal was noted on the density and absorption of samples.

However, a certain proportion of the coarse aggregate particles are elongated or flattened. Consequently, a preferential alignment is often visible on the surfaces of the cores. Mechanical anisotropy is therefore expected, or at least, it should be considered during the test program.

The characteristics of the two concrete mixtures used at RDI are presented in Table 1. The mix design initially specified contained a 38-76 mm aggregate fraction, but to facilitate concrete casting, a second mix design with a maximum 38 mm aggregate was also used.

3 AAR modelling of RDI

Since the degree of swelling associated with ASR measured with monitoring devices at RDI do not seem to slow down, it was considered necessary to evaluate the behavior of the main dam from a numerical modelling to reproduce its past and future behaviors. In order to achieve this goal, a numerical model had to be selected or developed. Although ASR has been studied intensively regarding physicochemical aspects, the effective consideration of the phenomenon at the structural level remains difficult. Over the past few years, there is a growing interest in this area given the many problems caused by this reaction. Moreover, the need for the rehabilitation of a structure affected by AAR should be supported as much as possible by quantifying the spatial distribution of concrete swelling, the analysis of the resulting stress state and the long-term projection of the effects of the evolution of the volumetric expansions. In recent years, some organizations have invested considerable resources in the development of numerical simulation models that can predict displacements, stresses and damage caused by AAR.

Simplified methods based on fictive thermal loading conditions which are used to reproduce the state of deformation given by the dam monitoring devices, do not provide an understanding of the actual behavior and stress distribution in the structure. In fact, these methods do not take into account the kinetic evolution of the chemical reaction as well as the nonlinear behavior of the concrete associated with the damage and creep. A need has been identified to develop a more rational approach for numerical simulation of volumetric expansion due to AAR using the finite element method (FEM) and computational power of today's computers.

After studying different models, it was considered advantageous to use the numerical model developed by Electricité de France (EDF) and established in Code_Aster[14] software. Adequate prediction of phenomena related to the expansion due to AAR requires to identify and to perform a realistic modeling of the physical, chemical and mechanical mechanisms.

It should be noted that among the phenomena related to volumetric change, creep in compression and tension plays a significant role. This has been reflected in the numerical model developed by EDF [15]. To enable easy formatting of this model in a finite element code, Code_Aster software was chosen. This is a numerical simulation software in structural mechanics developed by EDF since 1989. Code_Aster became a free software released under GNU GPL since October 2001.

Several test cases, based on experimental values or known answers were used to validate the numerical model of the AAR implanted under the BETON_RAG operator. It is also noteworthy that this model has been used by EDF for the numerical study of Temple-sur-Lot and Chambon dams. Like any numerical model, the operator requires knowledge of several parameters related to different phenomena considered by the model: mechanical, hydric, creep and AAR. These parameters have to be determined from a large number of tests performed in the laboratory. Table 2 summarize all the parameters (32) required by the BETON_RAG operator. They include typical mechanical properties as compressive and tensile strengths, elastic modulus, creep and hydric properties, etc. Some parameters (10) are strictly related to the AAR for the determination of the progression of the reaction ($\mathbf{A_0}$, $\boldsymbol{\alpha_0}$, **Ea**, $\mathbf{T_{ref}^{(\alpha 0)}}$, $\mathbf{Sr^0}$), the pressure effects ($\mathbf{b_g}$, $\mathbf{M_g}$, $\mathbf{V_g}$) and the viscoplastic deformation ($\boldsymbol{\varepsilon_0}$, $\boldsymbol{\tau_0}$).

The following sections summarize the laboratory test program related to the AAR tests started in 2015 for the Rapides-des-Îles power plant AAR modeling (see Figures 14 and 15). The complete program and test protocols are presented in Veilleux and Durand (2015)[3].

4 AAR testing program

4.1 Parameters associated with the AAR

To determine the parameters associated with the AAR, two types of tests are performed. The first type is free and confined expansion tests on cylinders of reconstituted concrete (38°C, 100% RH). It allows to determine the parameters related to AAR by a calibration process of the evolution of expansions under different stress states, except for the kinetic coefficient $\boldsymbol{\alpha_0}$. This parameter is rather estimated from mortar bar expansion tests for each class size of aggregates extracted from the cores coming from RDI dam, including the sand fraction (< 5mm) [16]. This mortar bar test is also performed with the original aggregate: its reactivity potential is 100% because it has not developed ASR yet (Age = 0) (60°C, 1N NaOH).

4.2 Reactive mortar bar tests (60°C, 1N NaOH)

As mentioned in the previous section, the reactive mortar bar test is used to determine the kinetic of the AAR for each aggregate class size. Indeed, it has been shown that the maximum expansion of individual particles is influenced by its size. Thus, for a given concrete affected by AAR for a given time, the chemical consumption of the reactive alkali-silica phases of a small aggregate particle is much larger than the one of a large aggregate particle. For the type of aggregate used in his tests, Multon et al. (2010) [17] had shown that the maximum expansion was obtained for a particle of about 700 μm. Since the size of the particle creating the maximum expansion depends on the type of aggregate [18], pre-qualification tests will be performed to determine the combination that provides the fastest expansion asymptotes in terms of mortar sand size and bar dimensions. The progression of chemical consumption is determined for each aggregate class size. In the case of RDI, four size classes will be used, namely: sand (< 5 mm), 5<D<19 mm coarse aggregate (3/4"), 19<D<38 mm coarse aggregate (1.5") and 38<D<76 mm coarse aggregate (3").

The aggregates for these tests will be obtained by extraction from RDI cores. This extraction was previously performed by etching with hydrochloric acid (35% HCl for 1 week). The hydrochloric acid is used to dissolve the cement paste and to recover the aggregates without significantly altering their composition. However, a new extraction procedure considered less aggressive is used by the LMDC[2] [19]. According to information obtained, this procedure consists now by manually crushing

[2] LMDC - Laboratoire Matériaux et Durabilité des Constructions de l'Université de Toulouse

concrete samples recovered into pieces about 5 cm and then heating them to 190°C for a period of 24 hours.

Thereafter, the pieces are immersed in a sodium sulfate solution 26% (Na_2SO_4) and five (5) thermal cycles are applied. Each cycle corresponds to the following variation of temperature: 3-4°C for 16 hours and then heating at 60°C for 8 hours. Afterwards, washing with hot water is performed. If extraction is not satisfactory, these 2 steps are repeated. The last step is to immerse the aggregates in a mixture of salicylic acid dissolved in methanol to remove any cement paste particles still adhering, followed by washing again with hot water. After three cycles of this chemical treatment, the recovered aggregates are washed again, dried and weighed. Finally, chemical analysis of the content of alkali and sulphates is carried out to confirm the state of aggregates extracted.

Alkali doped mortar bars are made with each aggregate class and exposed to 60°C in a 1N NaOH solution for a minimum of 6 months. To do this, each aggregate size class are crushed and sieved up to a particle size set at 0.16 to 1.25 mm. Initially, this size was set at 0.16 to 3.15 mm, the LMDC finds that it was better to use a finer particle size to optimize the expansions. The alkali content of the 25x25x285 mm mortar bars is increased to 8 kg/m^3 to enhance the expansion levels. The cement/aggregate ratio of the mortar bar is typical at about 0.33 whereas the water/cement ratio is the same as the RDI dam concrete.

At first, the mortar bar expansion results from unaltered reactive aggregates will be used to define the kinetic since the beginning (T=0) of the construction of the RDI dam for any aggregate class size. The basic idea is that current advancements are inversely proportional to the swelling mortars made from the non-altered original aggregate implicitly assuming that the entire available alkali reactive silica in the RDI dam concrete will be asymptotically available for the alkalies. Then, the amplitude of the asymptotic swelling is fitted in a manner that the simulated displacements are compatible with the monitoring data.

Note that only the kinetic ($\boldsymbol{\alpha_0}$) is estimated from tests on reconstituted mortar. The proposed methodology for concrete mortar passage is inspired by the approach originally presented in the thesis of Poyet (2003)[20]. A complete example of the procedure used to determine the parameters associated with the phenomenon of AAR is given in Grimal (2007) [15] for the concrete of the Temple-sur-Lot dam.

4.3 Tests on reconstituted reactive concrete cylinders (with the original coarse aggregate)

The parameters $\mathbf{A_0}$, $\mathbf{M_g}$, $\mathbf{b_g}$ and $\mathbf{Sr_0}$ are determined experimentally from a series of free and confined expansion tests (see Figure 16). The number of cases to consider is 9: free expansion (a), unconfined expansion under axial load of 8 and 16 MPa (b), confined expansion with steel rings of 3 mm thickness under axial load of 0, 8 and 16 MPa (c) and confined expansion with steel rings of 5 mm thickness under axial load of 0, 8 and 16 MPa (c). Note that the 8 and 16 MPa axial loads correspond to 40% and 80% of the specified 20 MPa compressive strength. (38°C, 100% RH or sealed specimens)

All samples are sealed with a double layer of plastic wrap and self-adhesive aluminum foil. The cylinders are placed in a climatic chamber at controlled temperature and humidity (38°C and 100% RH) the day before the zero reference measurement, which begin after 28 days of curing at 23°C (sealed and stored in a humid room). For samples under load, the zero reference measurement is carried out before loading.

The radial confinement is applied via 8 juxtaposed stainless steel rings of 3 mm and 5 mm thickness. In some previous tests made by Multon et al. (2010)[17], concrete was cast directly inside the rings and some problems associated with plastic shrinkage at ring-concrete interface were encountered. To prevent those problems, collar type rings will be installed after the curing period of the cylinders. The measurements will be carried out every two (2) weeks for a minimum period of 600 days. These measures consist of longitudinal and radial deformations on each cylinder in addition to mass measurements for free swelling reference cylinders.

For the identification of the parameter Sr^0, unsealed free expansion cylinders will be submitted to different relative humidity conditions. This will allow to determine the degree of saturation at which the chemical reaction cannot be initiated due to lack of moisture. Before proceeding with the determination of the parameters characterizing the shrinkage, it is recommended to determine the percentage of absorption, the density after immersion and the percentage of voids from non-reactive reconstituted concrete cylinders and also from the RDI cores. In addition, the degrees of saturation will be determined in situ on previously dry-drilled cores (without using water). These degrees of saturation serve as boundary conditions in a permeability analysis establishing the saturation field through the different parts of the dam.

For the fitting of the parameters, only the asymptotic expansion values are considered as a first step to calibrate the parameter $\mathbf{A_0}$, $\mathbf{M_g}$, $\mathbf{b_g}$ and $\mathbf{Sr_0}$. The $\boldsymbol{\alpha_0}$ kinetic parameter is fitted separately because of its great influence on the shape of the expansion curve. Thus, for each cylinder, the degree of saturation and the evolution of the longitudinal and transverse expansions have to be determined. Since the degree of saturation affects the kinetic and magnitude of the reaction, it is necessary to determined it precisely throughout the test by evaluating the mass variation of the samples.

The procedure of fitting the $\mathbf{A_0}$, $\mathbf{M_g}$, $\mathbf{b_g}$ and $\mathbf{Sr_0}$ parameters consists in minimizing the sum of square differences between the values of the measured and simulated expansions for all the tests carried out for the specified load conditions (see Figures 16 and 17). The minimization is done by using the generalized least squares method in order to obtain the best possible parameters fitting.

5 SUMMARY AND DISCUSSION

The Rapides-des-Îles hydroelectric power plant shows significant cracking and swelling. The main cause of these disorders has been identified as an alkali-silica reaction caused by the coarse aggregate which came from the rock excavation at RDI construction site.

The coarse aggregate (6 mm<D<76 mm), a mix of meta-greywacke and meta-siltstone, is very hard and resistant from the mechanical point of view but it tends to form during crushing a certain proportion of elongated and flattened particles. Its alkali reactivity is at first peripheral and, when the particles crack, continues with an "internal" attack. The sand fraction (<6 mm) from a glacial deposit, did not demonstrate alkali reactivity.

Early in RDI history, mechanical interventions took place on generating units to correct misalignments caused by concrete swelling resulting, among other things, to the ovalization of the unit wells. Several technical surveys were carried out in the 2000's based on 150x300 mm cores and mortar bar specimens made with a similar aggregate to the original aggregate. These surveys have confirmed an intense and always active alkali-silica reaction.

The numerical model for AAR simulation available in the Code_Aster software was selected in 2014 to evaluate the behavior of the main dam and to reproduce its past and future behavior. This numerical model requires the evaluation of 32 parameters characterizing the different phenomena: mechanics, creep, hydric and ASR effects.

An extensive test program was defined to provide the chemical and physico-mechanical parameters required by this numerical model. The tests will be made from 150x300 mm cores coming from 2 zones and also from concrete and mortar samples made with a coarse aggregate called "the original aggregate". The parameters of the chemical reaction progression will be determined from accelerated expansion tests on mortar (60°C, 1N NaOH), with aggregates extracted from the RDI cores and with the original aggregate, the latter allowing to know the potential for alkali reactivity in the initial state, i.e. since the construction of the dam. This ambitious experimental program started in 2015. It will require the completion of more than 500 tests and will take several years.

This paper summarizes the problem of concrete swelling at Rapides-des-Îles hydroelectric powerplant, presents the parameters required by the numerical model in Code_Aster software and describes in detail the test program planned to determine those parameters in a rigorous manner.

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TABLE 1: Concrete mixture design of Rapides-des-Îles power plant.

Constituents	1.5"-Mixture (kg/m^3)	3"-Mixture (kg/m^3)
"Type II" Portland Cement	242	227
Water	151	136
W/C	0.63	0.60
Air Entraining Agent (g)	41	41
Water Reducer (g)	1220	1220
Sand	720	707
6-19 mm Aggregate(1/4-3/4")	768	454
19-38 mm Aggregate (3/4-1.5")	513	627
38-76 mm Aggregate (1.5-3")	-	303
Total Aggregate	1281	1384
Total	**2395**	**2456**

TABLE 2: Model parameters.

<table>
<tr><th>Phenomena</th><th colspan="8">Parameters</th><th>Tests</th></tr>
<tr><td rowspan="5">Mechanical</td><td colspan="8">Elasticity</td><td rowspan="5">Compressive and traction under strain control</td></tr>
<tr><td colspan="4">E</td><td colspan="4">ν</td></tr>
<tr><td colspan="8">Rupture</td></tr>
<tr><td colspan="4">Compression</td><td colspan="4">Traction</td></tr>
<tr><td>Rc</td><td>ε^{c}_{peak}</td><td>l_c^{c}</td><td>δ</td><td>Rt</td><td colspan="2">ε^{t}_{peak}</td><td>l_c^{t}</td></tr>
<tr><td rowspan="3">Creep</td><td colspan="4">Spherical</td><td colspan="4">Deviatoric</td><td rowspan="3">Autogenous creep with unloading phase</td></tr>
<tr><td colspan="2">k_1</td><td colspan="2">η_1^{s}</td><td colspan="2">μ_1</td><td colspan="2">η_1^{d}</td></tr>
<tr><td colspan="2">k_2</td><td colspan="2">η_2^{s}</td><td colspan="2">μ_2</td><td colspan="2">η_2^{d}</td></tr>
<tr><td rowspan="4">Hydric</td><td colspan="8">$Sr < 1$</td><td rowspan="4">Shrinkage</td></tr>
<tr><td colspan="4">M_w</td><td colspan="4">b_w</td></tr>
<tr><td colspan="8">$Sr > 1$</td></tr>
<tr><td colspan="3">a</td><td colspan="2">b</td><td colspan="3">b_w</td></tr>
<tr><td rowspan="6">AAR</td><td colspan="8">Progression</td><td rowspan="6">Free and under load expansion</td></tr>
<tr><td colspan="2">A_0</td><td>α_0</td><td>Ea</td><td colspan="2">$T_{ref}(\alpha_0)$</td><td colspan="2">Sr^0</td></tr>
<tr><td colspan="8">Pressure</td></tr>
<tr><td colspan="3">b_g</td><td colspan="2">M_g</td><td colspan="3">V_g</td></tr>
<tr><td colspan="8">Viscoplastic deformation</td></tr>
<tr><td colspan="4">ε_0</td><td colspan="4">τ_0</td></tr>
</table>

FIGURE 1: Aerial view of Rapides-des-Îles dam.

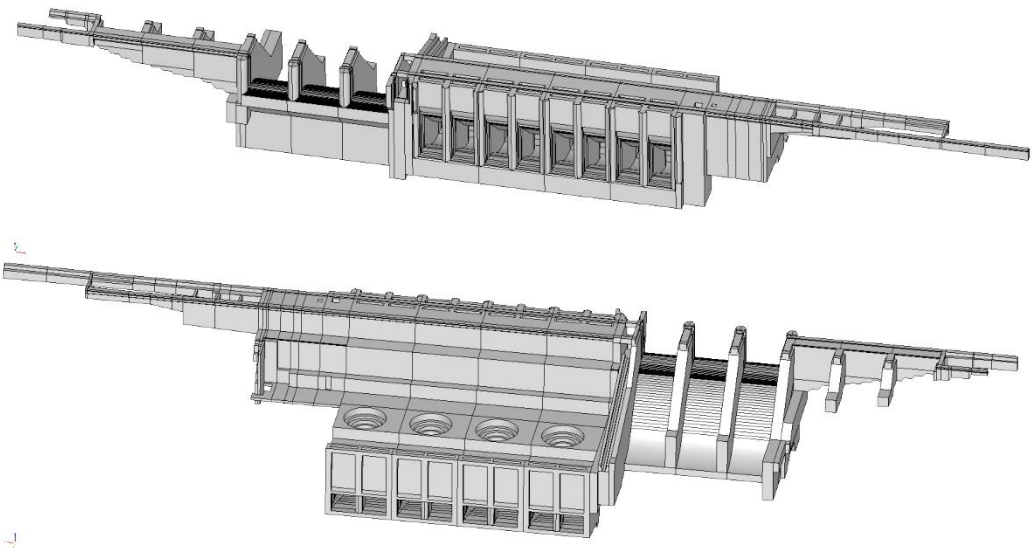


FIGURE 2: Upstream and downstream 3D views of Rapides-des-Îles power plant.

FIGURE 3: Downstream view of Rapides-des-Îles spillway piers showing map cracking.

FIGURE 4: Example of a badly cracked small concrete pole.

FIGURE 5: Example of diagonal cracks in a stair gallery.

FIGURE 6: Example of horizontal cracks in a drainage gallery.

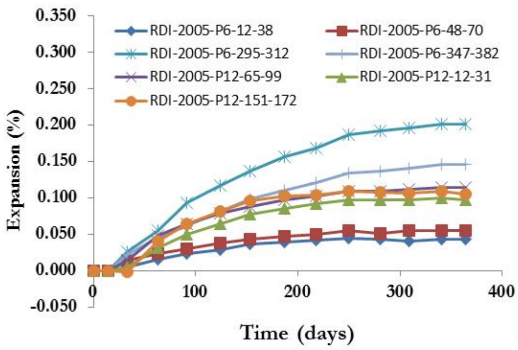


FIGURE 7: Typical 150-mm core expansion results at 38°C and 100% RH [13].

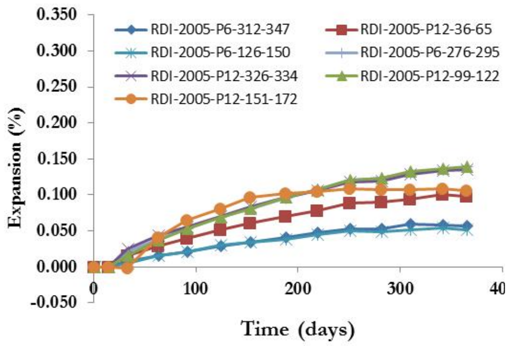


FIGURE 8: Typical 150-mm core expansion results at 38°C in 1N NaOH [13].

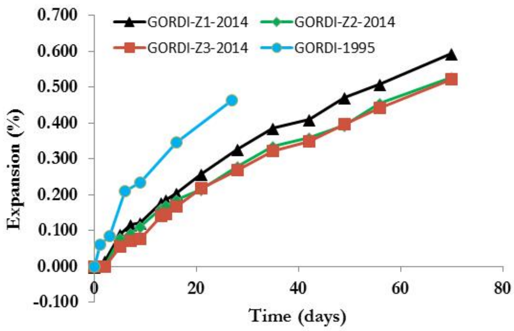


FIGURE 9: Expansion result at 80°C in 1N NaOH with the 1995 and 2014 original aggregate (CSA A23.2-25A).

FIGURE 10: Cracked aggregate with a rim of silica gel [11].

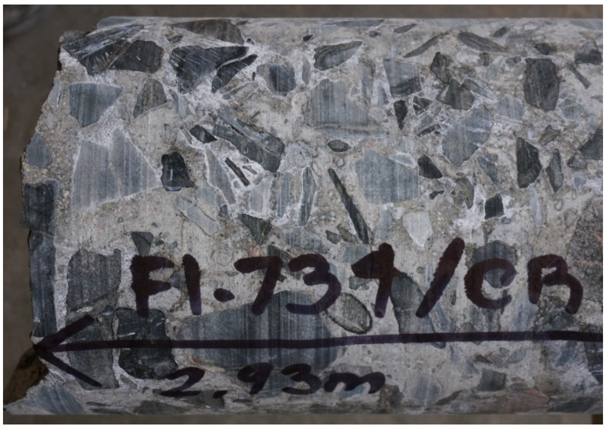


FIGURE 11: Example of core sections with typical aggregate showing some preferential orientation, elongated and flat, cracks and whitish deposits, also in the paste.

FIGURE 12: Example of a core section showing transverse cracks and whitish deposits in the paste.

FIGURE 13: Sample of 19-38 mm aggregate particles to be used as the original aggregate.

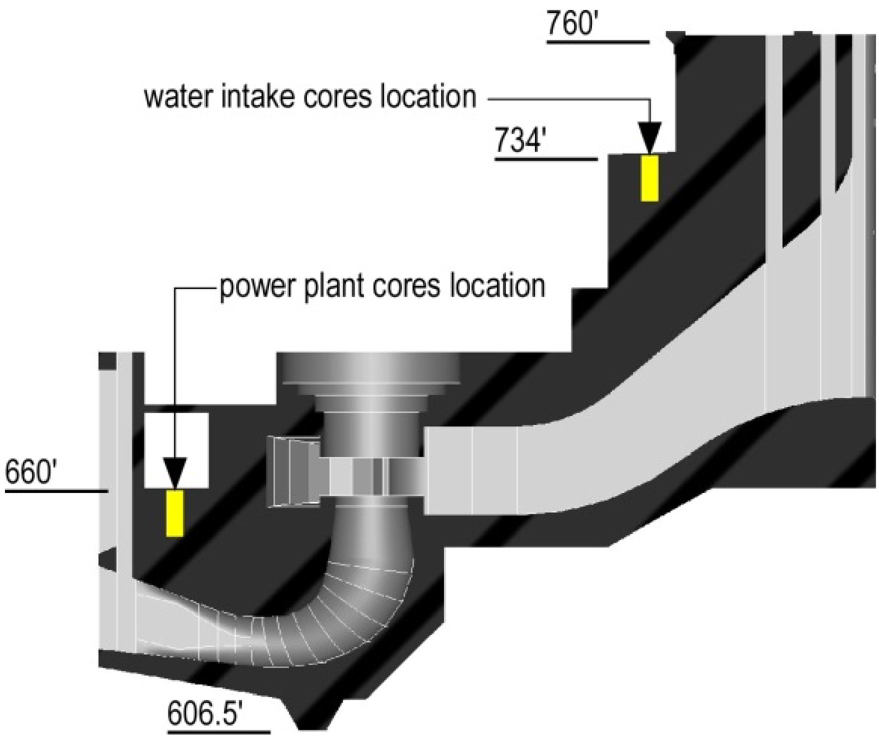
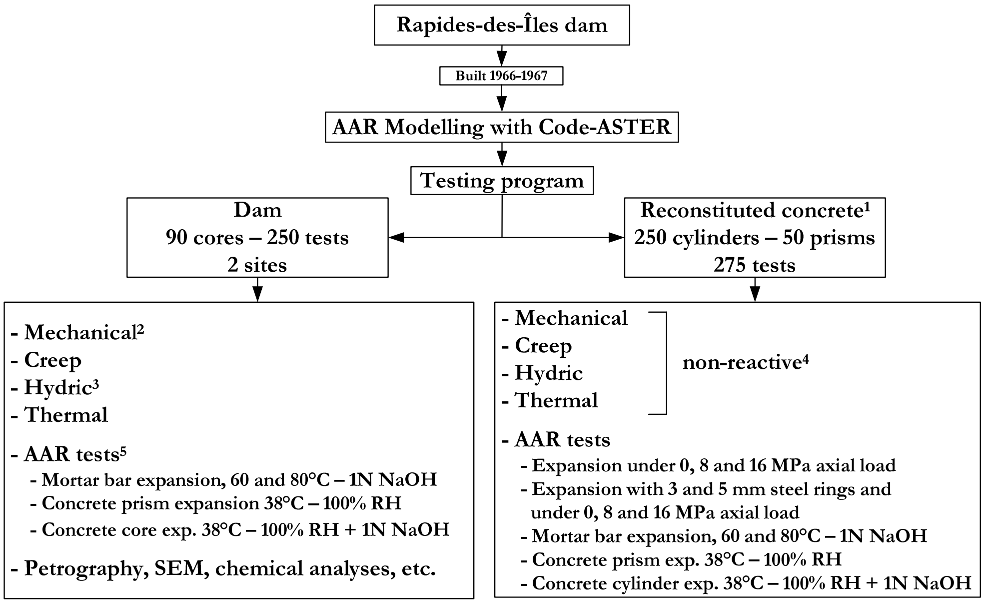


FIGURE 14: Location of the 2 sites where the series of 150 mm cores were taken for the test program (water intake section, level 734' and power plant section, level 660').



1- Concrete made to reproduced the original concrete mechanical and physical properties using the same aggregate as in the concrete of RDI dam – original aggregate.
2- Compressive, tensile and shear strenghts, elastic modulus and Poisson ratio and tensile fracture energy.
3- Swelling/shrinkage, porosity and permeability.
4- Specimens made with the original alkali-reactive aggregate using a very low-alkali cement in order to reproduce the initial properties of concrete.
5- Specimens made with the original alkali-reactive aggregate using a high-alkali cement to favor the development of ASR

FIGURE 15: Summary of the testing program.

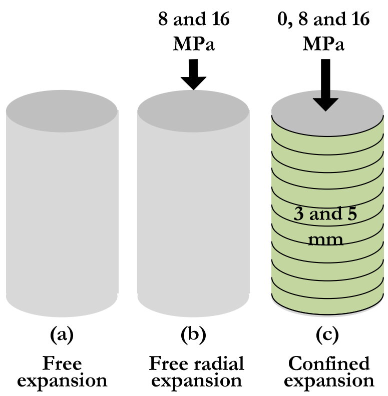


FIGURE 16: Loading configuration for original aggregate cylinders used for the determination of AAR parameters.

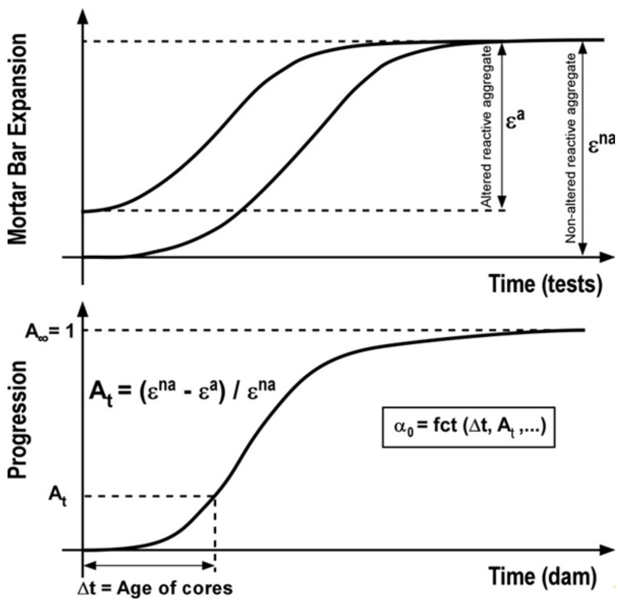


FIGURE 17: Diagram showing the relation between the progression of the alkali reaction and the expansions.