

## Alkali Aggregate Reaction in Nuclear Concrete Structures Part 1: A Holistic Approach

Nebojsa Orbovic<sup>1\*</sup>, Daman Panesar<sup>2</sup>, Shamim Sheikh<sup>3</sup>, Frank Vecchio<sup>4</sup>,  
Charles-Philippe Lamarche<sup>5</sup> and Andrei Blahoianu<sup>6</sup>

<sup>1\*</sup>Technical Specialist, Corresponding Author, CNSC-CCSN, Canada ([nebojsa.orbovic@cnscccsn.gc.ca](mailto:nebojsa.orbovic@cnscccsn.gc.ca))

<sup>2</sup>Associate Professor, University of Toronto, Canada ([d.panesar@utoronto.ca](mailto:d.panesar@utoronto.ca))

<sup>3</sup>Professor, University of Toronto, Canada ([sheikh@ecf.utoronto.ca](mailto:sheikh@ecf.utoronto.ca))

<sup>4</sup>Professor, University of Toronto, Canada ([fjv@ecf.utoronto.ca](mailto:fjv@ecf.utoronto.ca))

<sup>5</sup>Assistant Professor, University of Sherbrooke, Canada

([Charles-Philippe.Lamarche@USherbrooke.ca](mailto:Charles-Philippe.Lamarche@USherbrooke.ca))

<sup>6</sup>Director, CNSC-CCSN, Canada ([andrei.blahoianu@cnscccsn.gc.ca](mailto:andrei.blahoianu@cnscccsn.gc.ca))

### ABSTRACT

The Alkali Silica Reaction (ASR), a type of Alkali Aggregate Reaction (AAR), is observed in some concrete structures in Eastern Canada due to the presence of siliceous minerals in the aggregate used from the St. Lawrence River. CNSC staff is currently developing the basis for regulatory requirements with regard to the assessment of existing concrete structures with AAR as well as the means to avoid this pathology in new builds. A holistic approach was put in place in collaboration with the University of Toronto, and with a contribution of the University of Sherbrooke, to build technical background for these regulatory requirements. The intent of this paper is to present a general overview of this approach. The results presented in the series of papers are part of the first phase of the program and they are based on the test performed after first seven months of accelerated ageing. All specimens used in this program are reduced scale specimens. The goal is to assess their behaviour, material and mechanical properties at different stages of the reaction until its exhaustion. The development of AAR as a function of time in full scale specimens is out of scope of this paper. Leak-tightness of concrete structure with AAR is out of scope of this project as well. The output of this program will be used to establish a technical basis for the Canadian Nuclear Safety Commission's regulatory approach to deal with AAR in existing nuclear facilities as well as the regulatory measures to put in place to avoid this concrete pathology in new builds.

### INTRODUCTION

Taking into account life extension of Nuclear Power Plants (NPPs) there is a need to investigate degradations mechanisms of existing structures defining their aging management program. The Alkali Aggregate Reaction (AAR) is observed in some concrete structures in Eastern Canada due to the presence of siliceous minerals in the aggregate used from the St. Lawrence River. At this time, there is neither regulatory requirement nor industrial standard which addresses the impact of this reaction on nuclear structures. The chemistry of the reaction is relatively well understood; however, the potential mechanical consequences of the chemical reaction, in terms of ultimate resistance of structural elements and overall structural behaviour as a function of time, are not well known. There is a need to establish the relation between the chemistry of AAR, with its evolution in time, and structural mechanics.

## METHODOLOGY

The Canadian Nuclear Safety Commission put in place a holistic approach with three interconnected axis of research: material, structural and numerical simulation aspect.

With respect to the material aspect, (Guatam et al. (2015)), the goal is to perform testing program that determines the transient chemistry and mechanical properties of concrete samples subjected to accelerated environmental conditions for confined and unconfined specimens.

The structural aspect focuses on testing of squat shear walls, (Habibi et al. (2015), Lamarche et al. (2015)), as the most common structural elements in nuclear facilities. The structural tests related to the influence of AAR on the capacity of this type of structural elements are not reported in literature. The relation between chemical and mechanical properties shall be set up for concrete walls with the goal to define their ultimate capacity with the special accent on seismic ultimate capacity (alternated loading). Moreover, the relation between the mechanical properties of the concrete samples and the global structural behaviour is to be established. In the current codes and standards there are existing design relations between the concrete unconfined compressive strength and other concrete material properties (e.g. tensile strength, modulus of elasticity). Unconfined concrete strength is then used to define capacity of structural elements with an assumption that the capacity is proportional to the unconfined concrete strength (directly or to the square root). The destructive material and structural tests are set to assess whether the code relations are still valid in the case of concrete with AAR. If the existing relations are not valid, a possibility to establish new relations will be assessed. The design equations are based on unconfined concrete strength. In the case of the expending concrete due to AAR, special accent should be put on the effect of structural confinement due to overall structural effect (presence of surrounding structural elements) as well as to the effect of reinforcement and pre-stressing.

The walls are planned to be tested at three different levels of degradation using destructive and non-destructive methods. As in nuclear facilities destructive methods are not possible in most cases, a set of non-destructive methods are used with the goal to measure material properties as well as to correlate the material properties and the structural (shear walls) behavior. Destructive and non-destructive tests will be performed in order to propose reliable non-destructive tests.

The third aspect addresses numerical simulation and the validation of implemented models using the tests results, (Jurcut et al. (2015)). Numerical models will be calibrated on material tests and validated on structural tests for three different levels of degradations in order to establish reliable numerical tools for the structural assessment as well as for the prediction of the behaviour of structures with AAR.

The damaged walls will be then retrofitted using carbon fibres and tested again using destructive and non-destructive examinations to assess the effectiveness of the retrofit measure.

Based on all available test results, the acceptance criteria for structures affected with Alkali Aggregate Reaction, are to be established.

The program is performed by the University of Toronto with the participation of the University of Sherbrooke for non-destructive tests on shear walls.

### *Material aspect*

With respect to the material aspect, the goal is to execute developed testing program that determines the transient chemistry and mechanical properties (ultimate strength under compression and tension, elastic modulus and modulus of rupture) of concrete samples with AAR subjected to accelerated environmental conditions (50 °C and 95%-100% humidity). The specimens are kept under accelerated environmental conditions until exhaustion of the reaction. Both destructive and non-destructive test methods are being performed to evaluate the properties, as a function of time.

At material level, following tests are performed:

- Concrete prism test to characterize the reaction,
- Concrete cylinder test,
- Dog bone specimen tests,
- Cube specimen test to characterize expansion and degradation in mechanical properties for under different types of confinement.

The following tests measurements are performed with concrete prisms:

- Expansion (longitudinal and transversal),
- Dynamic modulus of elasticity,
- Damage Rating Index (DRI)
- Modulus of rupture test,
- Water absorption test,
- Resistivity

Two types of concrete prism tests are performed 1) the standard ASTM C1293 concrete prism test (CPT) and 2) an accelerated concrete prism test (ACPT) performed at 50 °C.

The damage rating index (DRI) correlated well with expansion in both tests. The expansion occurred faster in the accelerated version and DRI for ACPT test was observed larger than that for CPT as higher temperature was found to cause larger number of cracks, (Panesar et al. (2014)). Destructive test performed with concrete prisms is modulus of rupture test. Non-destructive tests of concrete prisms performed are: ultrasonic pulse velocity (UPV) and transverse resonant frequency for dynamic modulus of elasticity, (Panesar et al. (2014)).

### *The results of Expansion test*

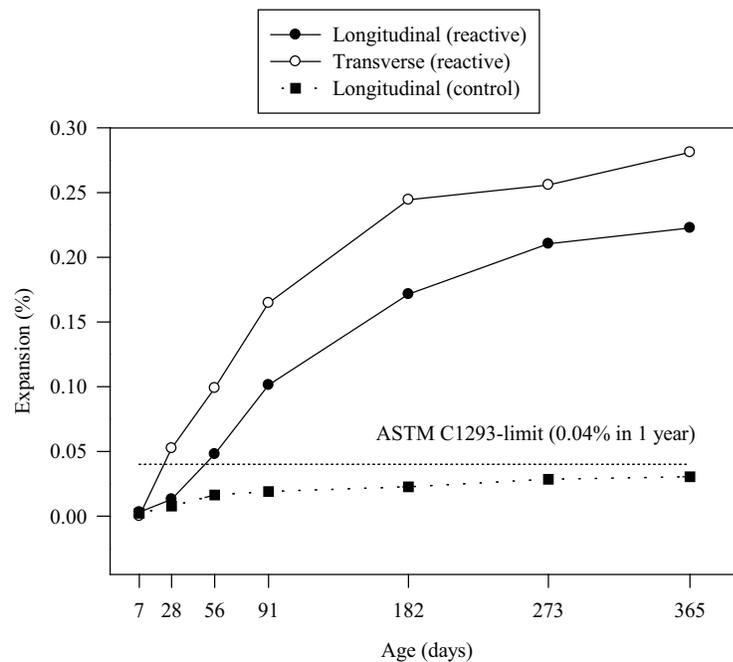


Figure 1 Average longitudinal and transverse expansion of the concrete prisms (Panesar et al. 2014)

The expansion measurements are plotted in Figure 1. The figure presents the plot of longitudinal and transverse expansion measurements for prisms made with reactive aggregate and non-reactive

aggregate (control specimens). The expansion of control prisms remains below the 0.04% limit for the non-reactive aggregate as indicated by ASTM C1293 (2008) (Panesar et al. 2014).

*Effect of AAR on concrete properties*

Table 1. Effect of AAR on concrete properties

Age (days)	Expansion, %	Expansion class	DRI	Degradation in MOR	Degradation in $E_{dyn}$ by UPV	Degradation in $E_{dyn}$ by resonant frequency
28	0.01%	Negligible	123	0%	0%	0%
56	0.05%	Marginal (onset of cracking)	209	42%	0%	4%
365	0.22%	High	614	58%	8%	13%

Table 1 shows the degradation in concrete properties due to AAR for one year as tested for the program outlined in Gautam et al. (2015). DRI and expansion are seen to increase with age. High level of expansion is observed in one year. MOR and the dynamic modulus of elasticity are seen to degrade with age owing to AAR degradation. The degradation is assumed as starting at the age of 28 days even though the actual degradation might have initiated beforehand. MOR appears to suffer the most due to AAR (Panesar et al. 2014).

Concrete cylinder tests are: unconfined compressive strength, split tensile strength, Poisson's ratio and static modulus of elasticity test. The results of unconfined compressive strength and static modulus of elasticity tests are presented in Figure 2 and Table 2 using the same concrete as in shear wall tests (Habibi et al. 2015). Dog bone specimen tests are performed in order to determine concrete tensile strength with direct tensile tests (Habibi et al. 2015). The results indicate that the regular concrete with tensile capacity of 4.76 MPa has 47% higher capacity than the AAR concrete with tensile strength of 3.24 MPa.

A series of cube specimens is tested in order to monitor cube expansion in three directions for free and restrained (uniaxial and bi-axial loading) specimens. The change in dynamic modulus of elasticity based on UPV is monitored as well. As part of destructive testing, the core drilling of the cube specimen was performed. The drilled cores are tested for compressive strength, modulus of elasticity and Poisson's ratio (Gautam et al. 2015).

Based on the tests from the first phase of this project, the unconfined concrete strength was least affected among studied concrete properties. Among three concrete properties used in the design (unconfined compressive strength, splitting tensile strength and static modulus of elasticity) unconfined concrete strength is the only one which did not decrease after accelerated curing comparing to the initial value.

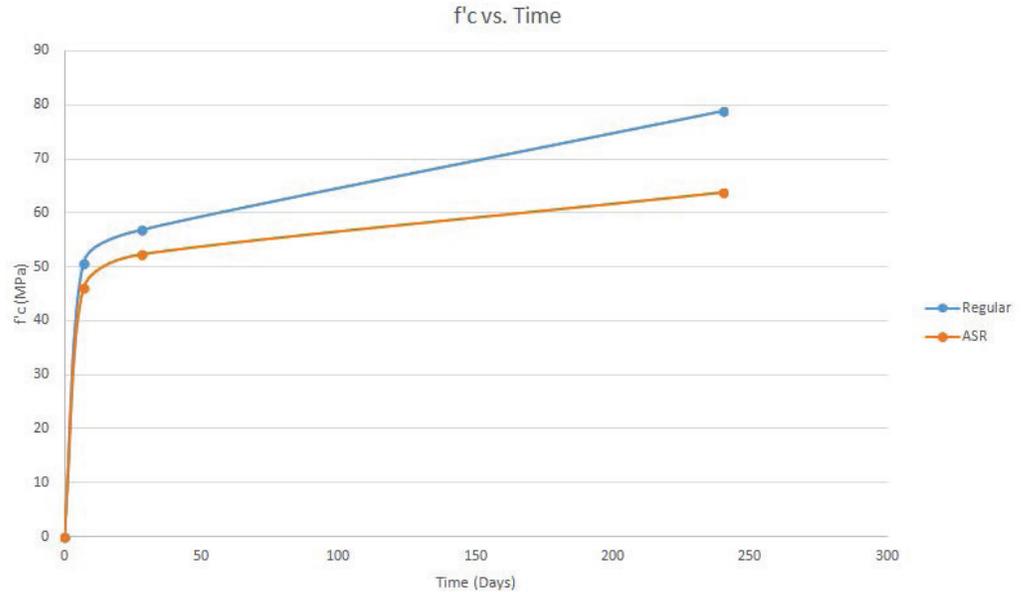


Figure 2. Unconfined concrete compressive strength for regular and AAR specimens (Habibi et al. (2015))

Table 2. Summary of Elastic modulus of regular and AAR concrete over time (Habibi et al. (2015))

<i>Age (days)</i>	<i>Elastic Modulus of REG (MPa)</i>	<i>Gain %</i>	<i>Elastic Modulus AAR (MPa)</i>	<i>Loss %</i>
0	0	N/A	0	N/A
7	33400	N/A	40950	N/A
28	35150	5.2	37700	7.9
240	47150	34.3	35750	5.2

### ***Structural aspect***

The structural aspect focuses on destructive and non-destructive testing of squat shear walls, as the most common structural elements in nuclear facilities. The wall design with barbells as boundary elements and strong horizontal beams, Figure 2, was chosen based on previously performed tests in Bouchon et al (2004) in order to obtain a known failure mechanism. The walls are designed using code equations for shear-friction in order to obtain the failure through the wall and to avoid the failure on the contact of the wall with the beam. Six walls are casted and, similar to the specimens for material testing, they are subjected to accelerated ageing in an environmental chamber with 50 °C and 95%-100% humidity.

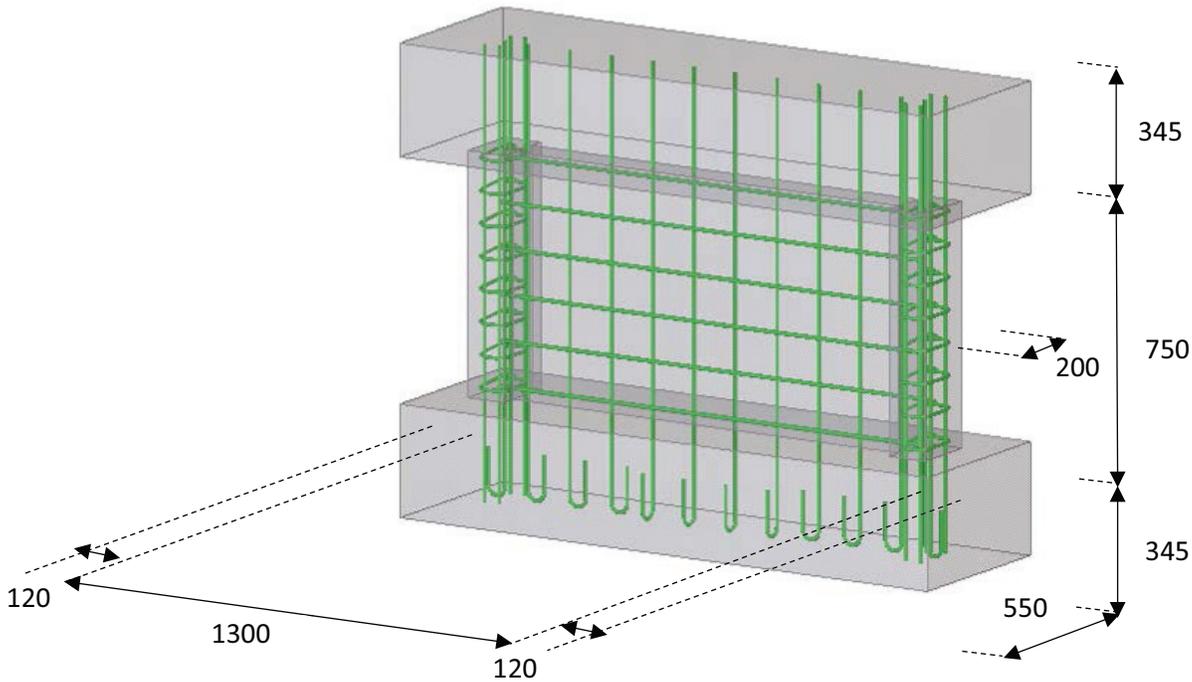


Figure 2. Geometry and reinforcement of shear wall specimen

The goal of this test campaign is to focus on the differences in the behaviour and capacity of a wall made of sound concrete and the wall with AAR. The walls (two walls in one testing campaign) are planned to be tested at three different levels of degradation using destructive and non-destructive methods.

#### *Destructive – Static Cyclic Loading Tests*

The goal of destructive examinations is to determine mechanical characteristics such as: ultimate resistance, ultimate displacement, ductility, residual strength of walls with AAR (compared to sound walls) as well as to correlate the level of damage in terms of crack spacing and crack width with the structural drift (Habibi et al. (2015)).

A preliminary finite element analysis of the walls suggested that it would require about 900 kN to 1100 kN lateral load to fail the specimens. This requires the use of two actuators with 1000-kN capacity. Figure 3 shows the test setup for the shear wall specimen. Both actuators will be active simultaneously in applying the lateral load so that the loading pattern in both directions is similar. The wall will be anchored to the “strong floor” with the help of two high strength bolts. In addition, there will be support keys on both sides of the bottom beam to provide additional reaction. Axial load will be maintained throughout the test with the help of an 800-kN jack (Habibi et al. (2015)).



- 2) For modal analysis two different methods are performed:
  - 2.1) Frequency response function method;
  - 2.2) Basic frequency domain method.

The frequency response function method deals with the analysis of the output acceleration and the input excitation force, which in this case is a hammer blow. This method is generally implemented in a laboratory environment because measuring the force input on a specimen is not always easy to do during on-site tests. The second method is an output only method that does not take the force measurement into account. This type of method is better suited for field testing.

The results in terms of resonant frequencies in longitudinal direction are presented in Table 2 for Frequency response function method. The frequency decrease of 8.1% for AAR wall was recorded. The same results are obtained using Basic frequency method.

Table 2 Resonant frequency shifts

Mode	NR (Hz)	AAR (Hz)	Diff. (%)
1	584.6	516.9	-11.6
2	734.3	680.9	-7.3
<b>3</b>	<b>1235.0</b>	<b>1135.8</b>	<b>-8.1</b>
4	1504.9	1413.3	-6.1
5	1783.4	1665.1	-6.6
6	1859.7	1734.7	-6.7
7	2405.2	2155.3	-10.4
8	2669.3	2526.3	-5.4

In terms of damping ratios, the damping ratio for regular wall was 0.336% and for AAR wall was 0.653%, or an increase of 94% (Lamarche et al. (2015)).

### *Numerical Simulations*

The third aspect addresses numerical simulation and the validation of implemented models using the tests on squat walls (Habibi et al. (2015)) with material properties from material tests as indicated in Guatam et al. (2015). The simulation will be carried out using VecTor software developed at the University of Toronto. VecTor2 is a two-dimensional finite element program for the analysis of reinforced concrete membrane structures under static and dynamic loading. The Modified Compression Field Theory (MCFT) and the Disturbed Stress Field Model (DSFM), analytical models for reinforced concrete elements subjected to in-plane normal and shear stresses, form the basis for VecTor2. The program has been enhanced to take into consideration the effects of lateral expansion, triaxial stresses, cyclic loading, construction and loading chronology, and bond-slip (Jurcut et al. (2015)).

To simulate the AAR effects on the structural behaviour of reinforced concrete elements, two mechanisms are considered in VecTor2: induced expansion, and accompanying changes in mechanical properties.

The AAR-induced expansion is treated using methods developed previously for elastic and plastic strain offsets (Jurcut et al. (2015)). In this formulation the material prestrains are considered in the definition of the material stiffness matrix and element nodal forces. Strain offsets are taken into account in the analysis by defining pseudo-stresses reapplied to the element within an iterative algorithm. This procedure has been used to successfully model post-cracking Poisson's effects, shrinkage, and thermal expansion. However, AAR effects are significantly different from the volume change mechanisms simulated so far with VecTor2. They are directional and time-dependent; long-term stress history

influence the magnitude and orientation of AAR strains rather than the instantaneous stress condition, representing a substantially more complex situation.

Changes in the mechanical properties of concrete (i.e., tensile strength, compressive strength, and modulus of elasticity) are evaluated as percentages of the respective properties of unaffected concrete at 28 days as functions of the free expansion. The lower bounds to the residual properties were implemented from (ISE (1992)). More recent studies have shown that a direct correlation between the level of expansion and the change in mechanical properties is insufficient due to the multiple factors involved in their evolution in time including environmental conditions and aggregate type. Once the material-level investigation (Guatam et al. (2015)) is finalized, more accurate reduction functions will be implemented in VecTor2 (Jurcut et al. (2015)).

## **DISCUSSION**

In the first phase of the current program (220-240 days after pouring concrete) a set of tests material and structural was performed in order to assess the differences between the regular concrete specimens and the specimens with AAR. At the material level, the unconfined concrete strength was least affected among studied concrete properties. Among three concrete properties used in the design (unconfined compressive strength, splitting tensile strength and static modulus of elasticity) unconfined concrete strength is the only one which did not decrease after accelerated curing comparing to the initial value.

In structural tests on shear walls all three concrete material properties used in design were lower in the wall with AAR than in the wall with regular concrete. Modal analysis showed lower resonant frequencies (-8.1%), consistent with the lower modulus of elasticity (-24%), and higher damping of the wall with AAR. However, the destructive structural tests showed higher capacity (+14.8%) of the shear wall with AAR than the regular one. Therefore, based on this test, the code relations between the material properties (e.g. unconfined compressive strength) and the structural capacity (e.g. shear capacity) are not valid for shear walls with boundary elements affected by AAR and with approximately 0.18% expansion. One explanation is that the AAR induced concrete expansion introduces confining stresses in the shear wall due to the presence of boundary elements (massive beams and barbells) and the reinforcement. This explanation needs to be justified and the confinement quantified in the subsequent phases of this project with two higher levels of reaction. Moreover, the level of confinement and its impact on the variation of wall shear capacity, as a function of AAR development, should be assessed. The AAR induced expansion introduces additional parameters which make the assessment of structural capacity more complex.

## **CONCLUSION**

In the current design codes and standards there are established relations between the concrete unconfined compressive strength and other concrete material properties (e.g. tensile strength, modulus of elasticity). Unconfined concrete strength is then used to define capacity of structural elements with an assumption that the capacity is proportional to the unconfined concrete strength. Based on the results of the first phase of this program, these relations are not valid for the structural elements with AAR due to the elements confinement induced by concrete expansion.

For this reason it is necessary in the following phases of this program to 1) assess the level of confinement as a function of AAR and the possibility of establishing relations between concrete material properties and the capacity of shear walls as a function of this confinement and its evolution in time, 2) propose reliable non-destructive methods in order to assess the condition of the concrete structures with AAR, 3) establish acceptance criteria for ultimate shear capacity and 5) predict the future behavior and acceptable limits.

The outcome will be used as a technical basis for the CNSC regulatory approach related to the existing nuclear facilities with AAR as well as the regulatory measures to put in place to avoid this concrete pathology in new builds.

## REFERENCES

- Gautam, B., et al. (2015) 'Alkali Aggregate Reaction in Nuclear Concrete Structures: Part 2: Concrete Materials Aspects' submitted to SMiRT 23, Manchester, U.K.
- Habibi, F., et al. (2015) 'Alkali Aggregate Reaction in Nuclear Concrete Structures: Part 3: Structural Wall Element Aspects' submitted to SMiRT 23, Manchester, U.K.
- Jurcut, A., et al. (2015) 'Alkali Aggregate Reaction in Nuclear Concrete Structures: Part 4: Modelling and Analysis' submitted to SMiRT 23, Manchester, U.K.
- Lamarche, C-Ph., et al. (2015) 'Alkali Aggregate Reaction in Nuclear Concrete Structures: Part 5: Non-destructive dynamic methods for structural assessment' submitted to SMiRT 23, Manchester, U.K.
- Bouchon, M. et al. (2004) Tests on Reinforced Concrete Low-Rise Shear Walls under Static Cyclic Loading, 13 WCEE, Vancouver, Canada,
- Panesar, D. K., Sheikh, S. A., and Vecchio, F. J. (2014). *Investigation of consequences of concrete alkali aggregate reaction on existing nuclear structures: Progress Report #5* to CNSC. Toronto, Canada,
- Institution of Structural Engineers (ISE). (1992). "Structural Effects of Alkali-Silica Reaction", SETO, London.